Loads and response from steep and breaking waves on monopiles

Bredmose, Henrik; Schløer, Signe; Sahlberg-Nielsen, Lasse; Slabiak, Peter ; Larsen, Torben J.; Kim, Taessong ; Paulsen, Bo Terp; Bingham, Harry B.; Jacobsen, Niels Gjøl; Tornfeldt Sørensen, Jacob

Total number of authors:
12

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Loads and response from steep and breaking waves on monopiles

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Statkraft

With contributions from
Henrik Bredmose
Signe Schløer
Lasse Sahlberg-Nielsen
Peter Slabiak
Torben J. Larsen
Taessong Kim
Bo Terp Paulsen
Harry Bingham
Niels Gjøl Jacobsen
Jacob Tornfeldt Sørensen
Flemming Schlütter
Anders Wedel Nielsen
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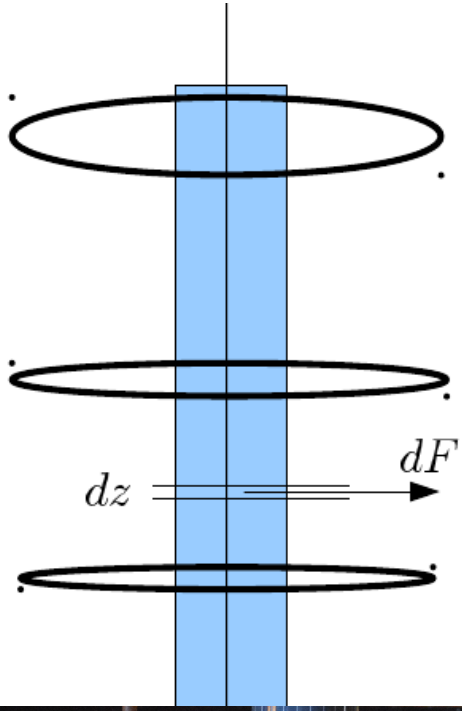
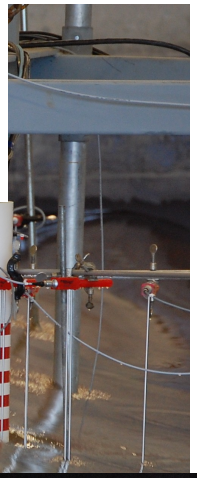
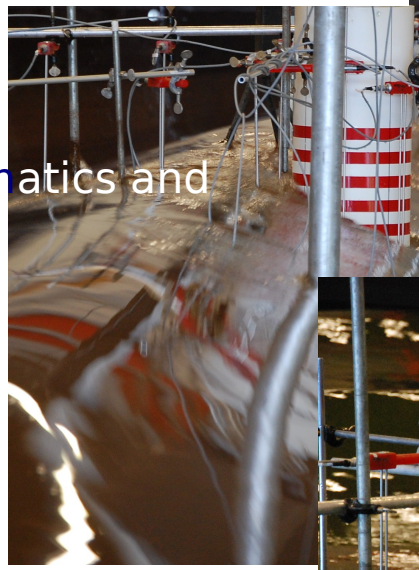
Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation

$$F = \frac{1}{2}\rho C_D D|U|U + \rho C_M A\frac{dU}{dt}$$







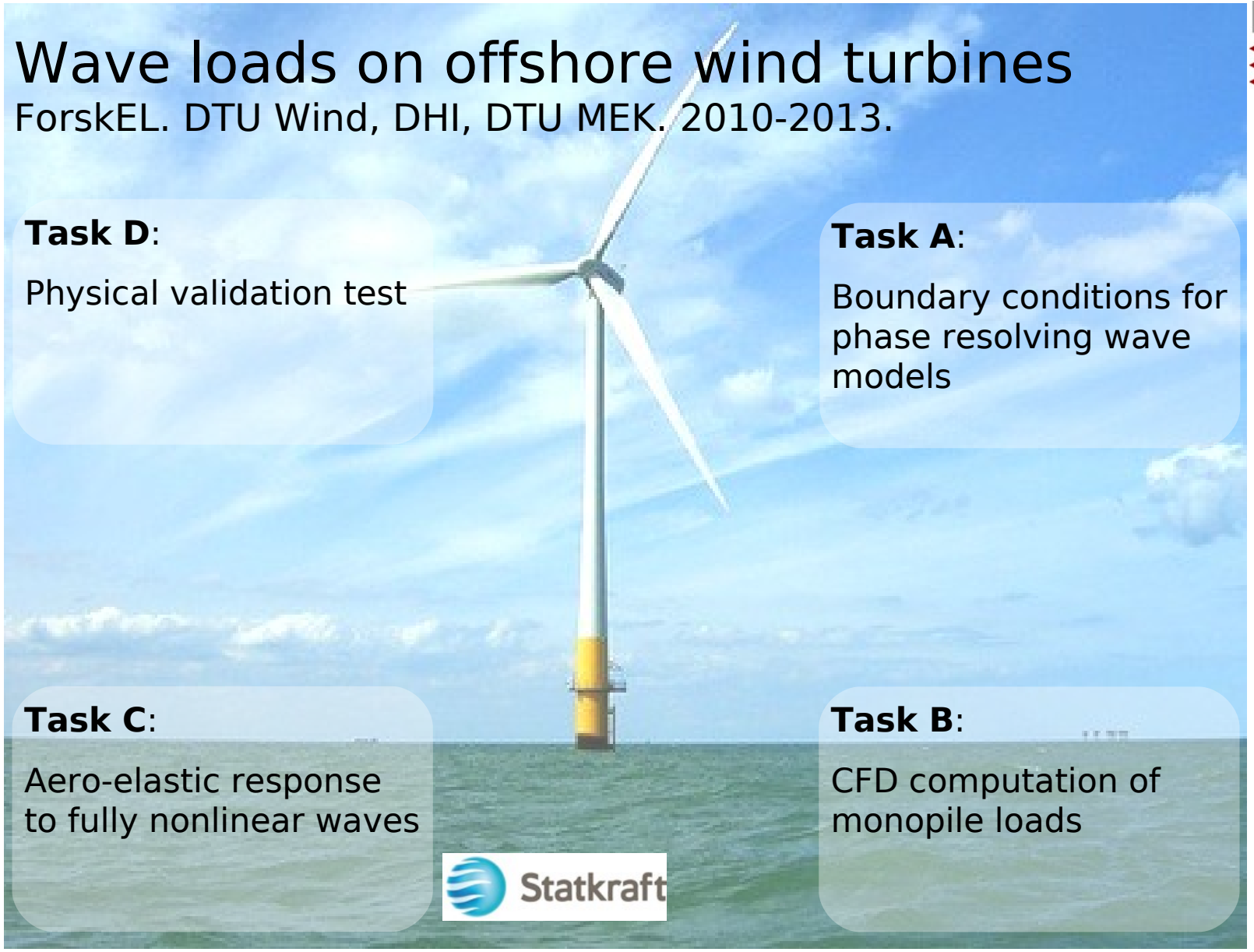
Better: Fully nonlinear wave kinematics and Morison equation

Advanced: CFD and coupled CFD

Zang ar

Wave loads on offshore wind turbines

ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.



Task D:

Physical validation test

Task A:

Boundary conditions for phase resolving wave models

Task C:

Aero-elastic response to fully nonlinear waves

Task B:

CFD computation of monopile loads

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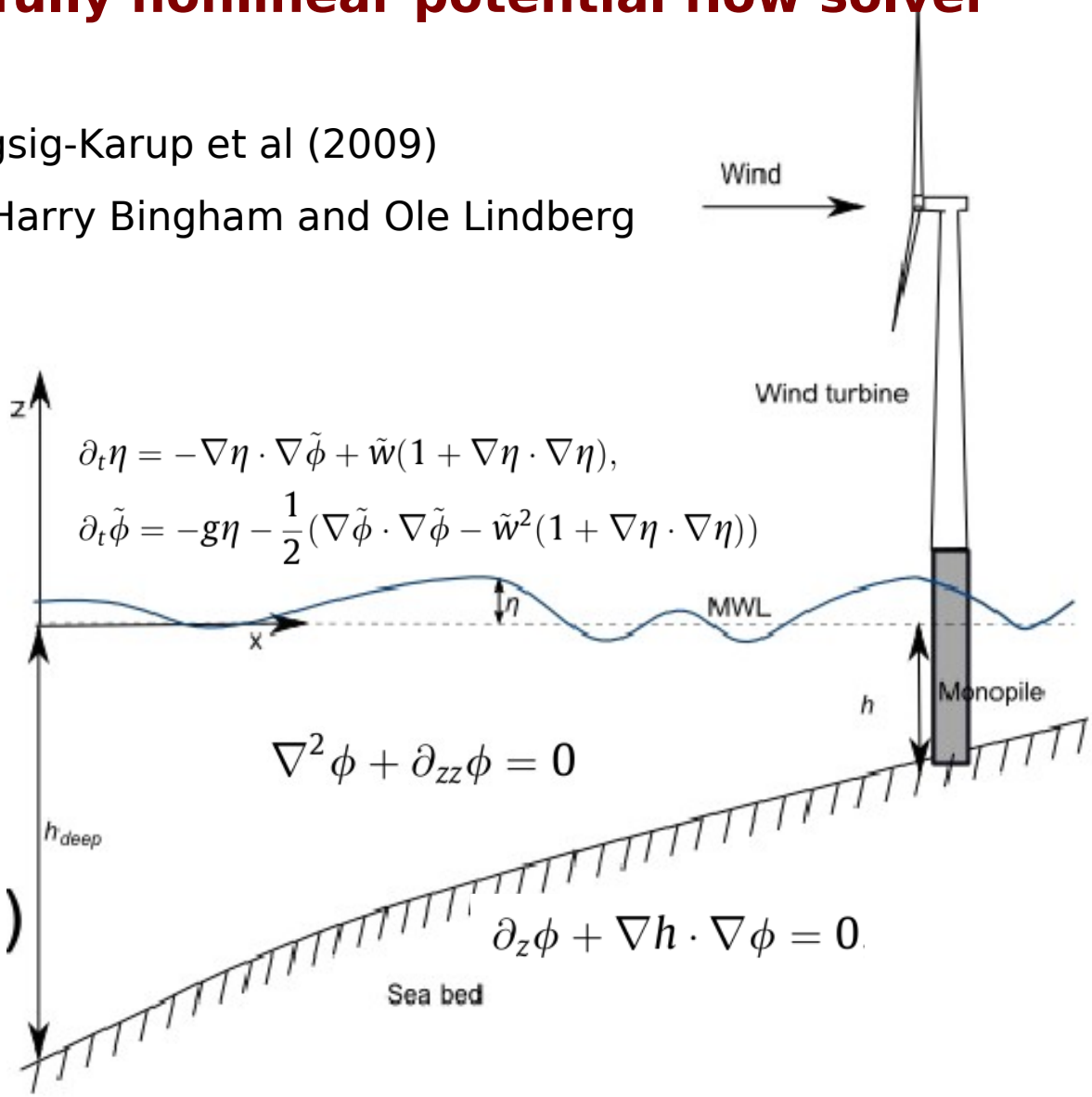
Forces from a fully nonlinear potential flow solver

'OceanWave3D', Engsig-Karup et al (2009)

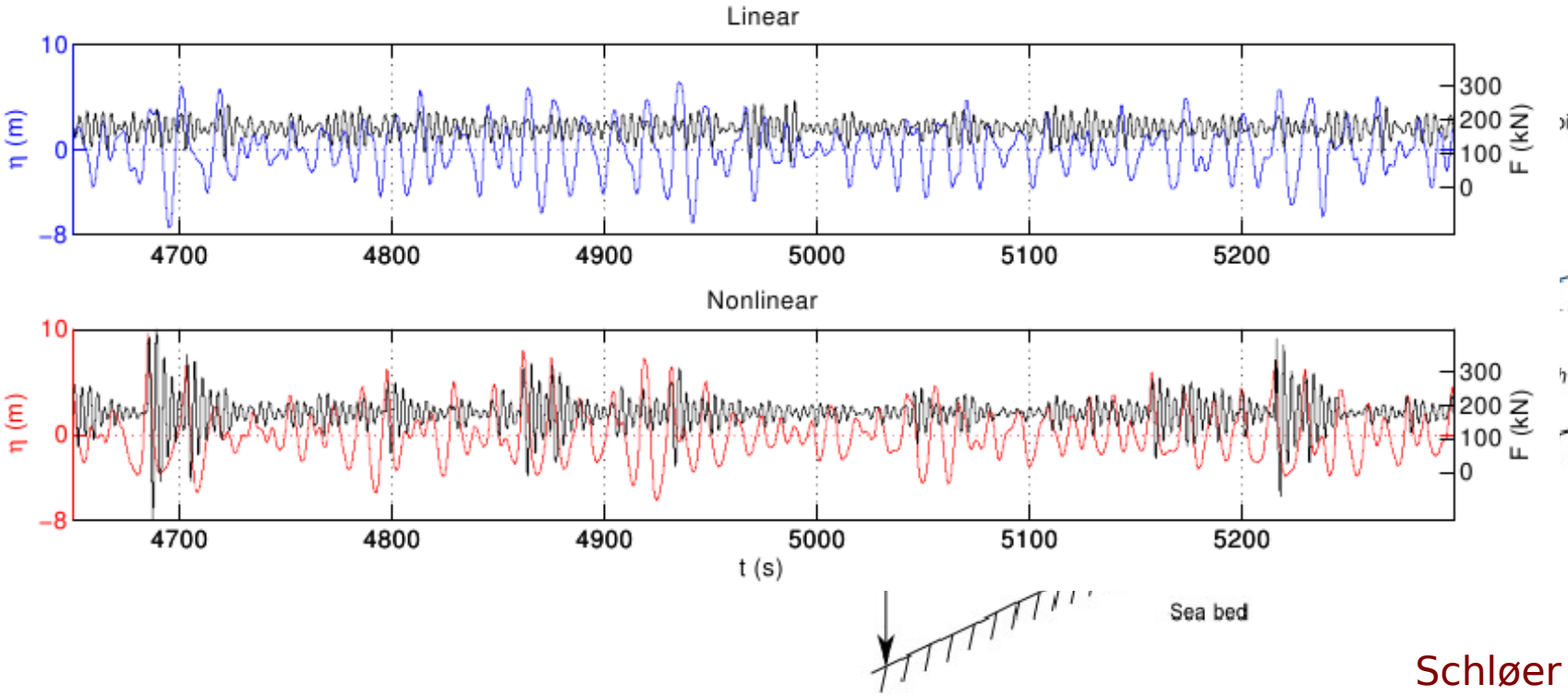
Allan Engsig-Karup, Harry Bingham and Ole Lindberg



Response in bottom of tower

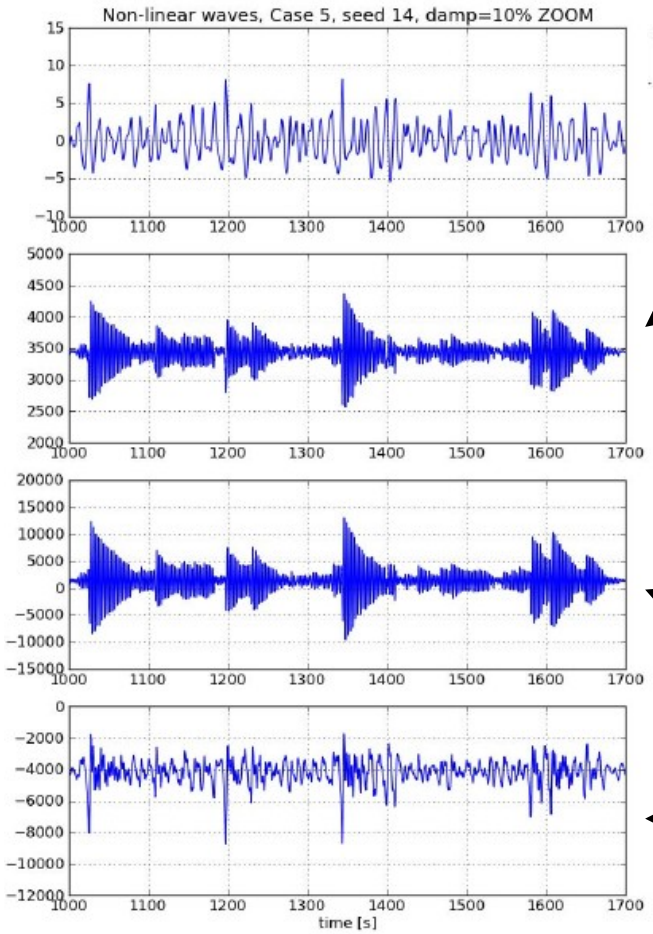
Fully nonlinear waves versus linear waves

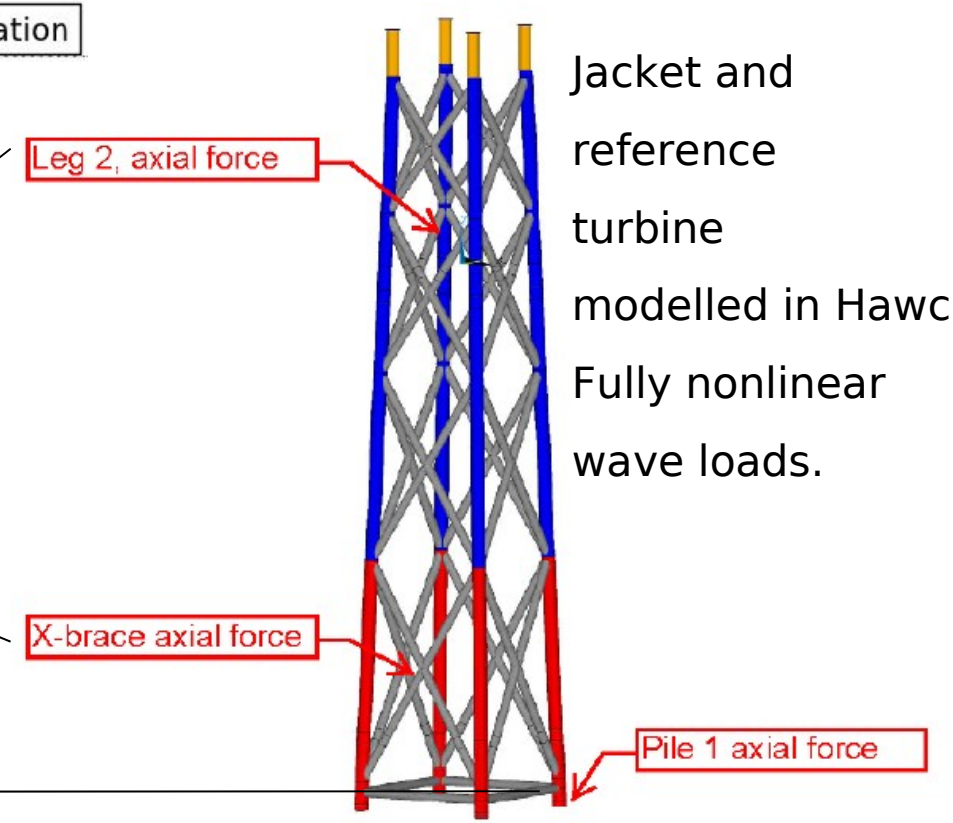
$H_s = 9.4\,\mathrm{m},\ T_p = 14.2\,\mathrm{s},\ W = 5\,\mathrm{m/s}$



Schløer et al
(OMAE 2012)

The OC4 jacket





Jacket and reference turbine modelled in Hawc2. Fully nonlinear wave loads.

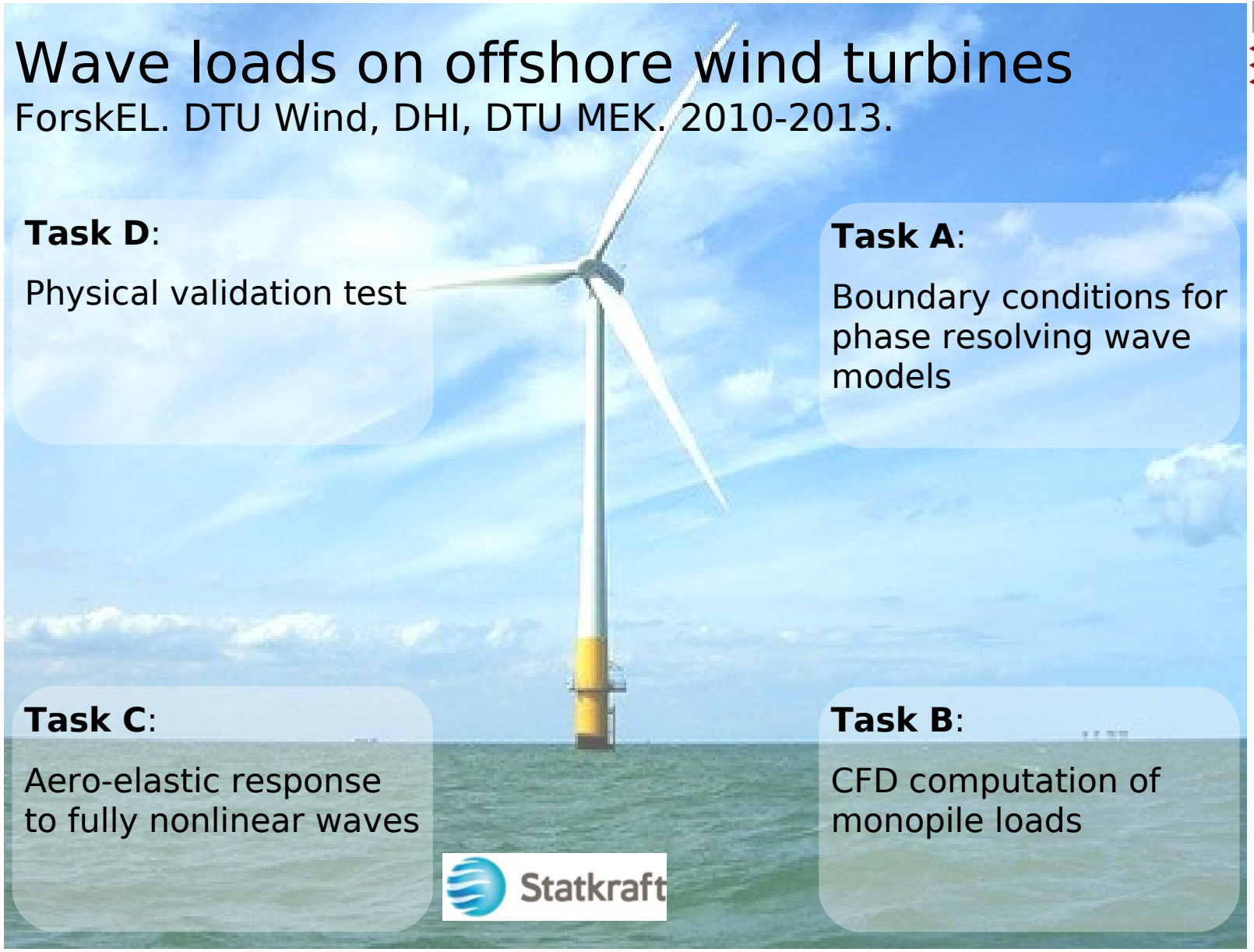
Storm sea state. Turbine standstil.

Severe ringing/impulsive excitation.

Torben Juul Larsen
Taesong Kim
Larsen et al Europ. Offsh. Wind 2011

Wave loads on offshore wind turbines

ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.



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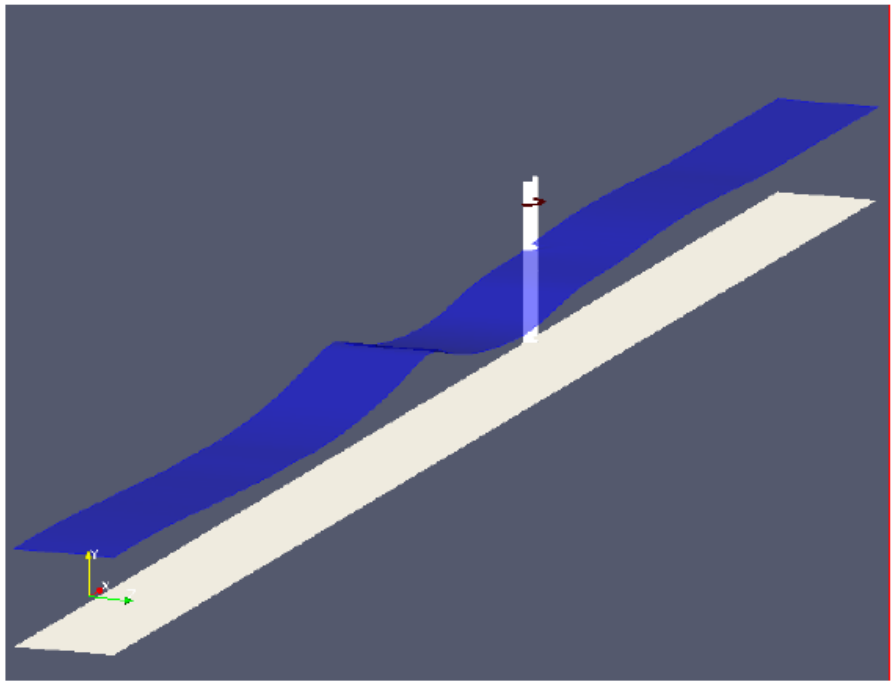
The OpenFOAM® CFD solver

Open source CFD toolbox

Vast attention during last 3 years

This study: interFoam solver

- 3D incompressible Navier-Stokes
- two phases (water and air)
- VOF treatment of free surface

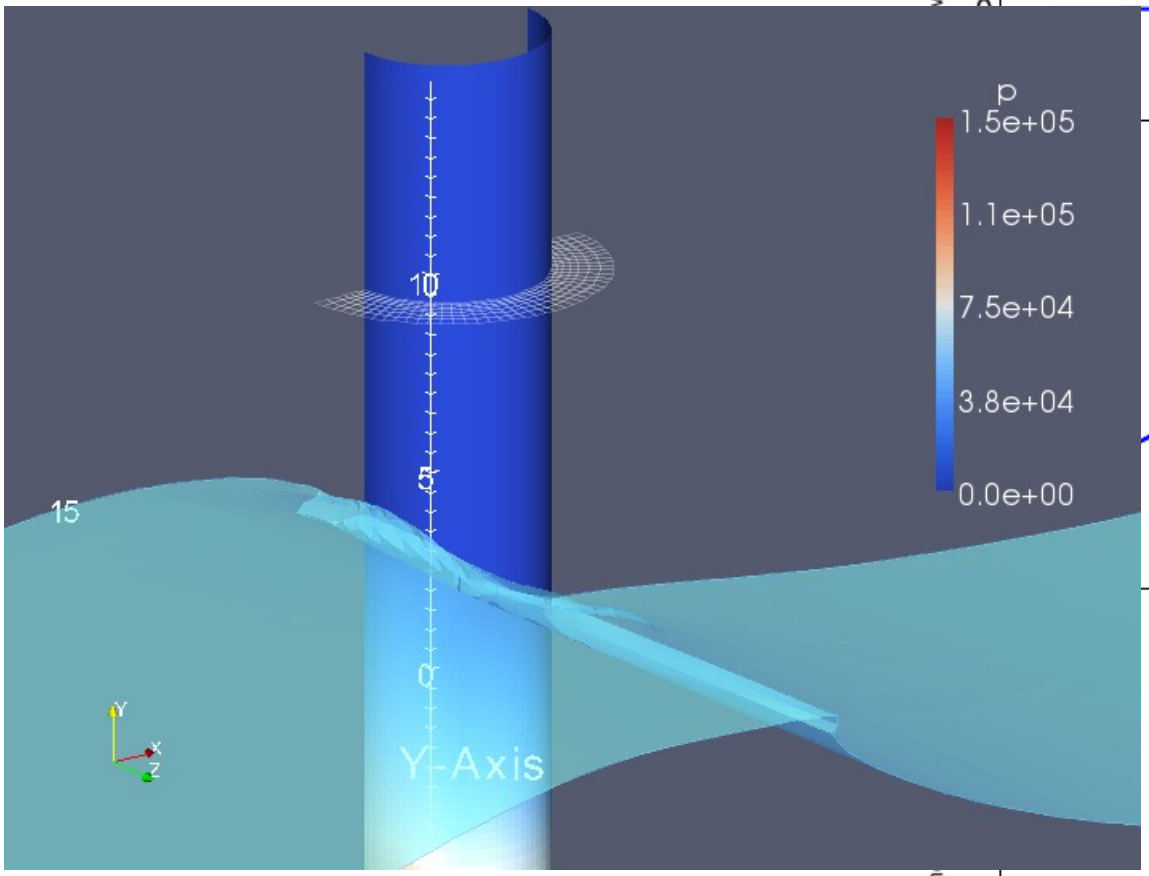


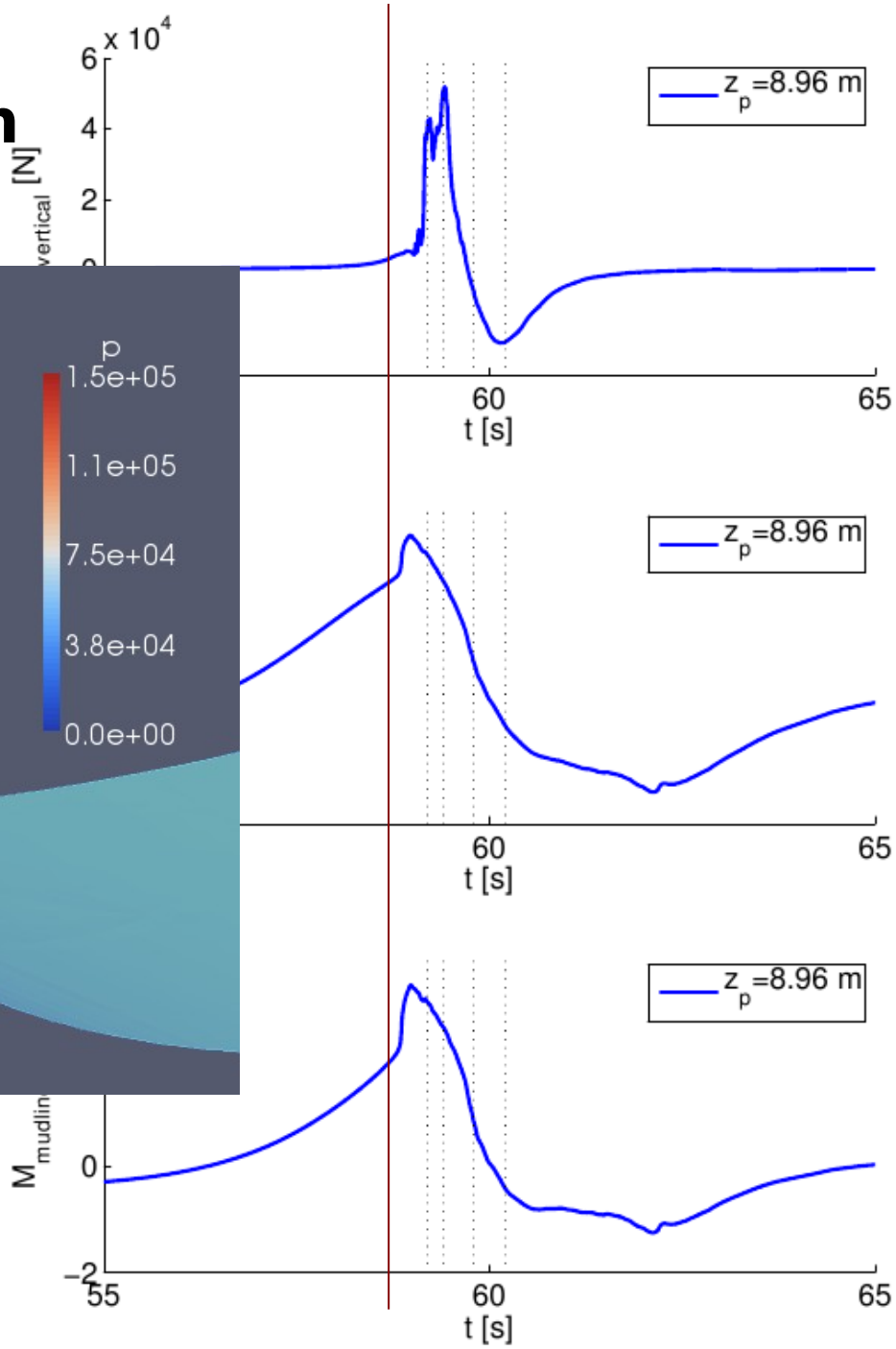
Waves2foam wave generation toolbox has been developed and validated

(Niels Gjøl Jacobsen

PhD thesis 2011; Paper in Int. J. Num. Meth. Fluids)

Platform height of 8.96m





t=58.8s

Bredmose & Jacobsen OMAE 2011

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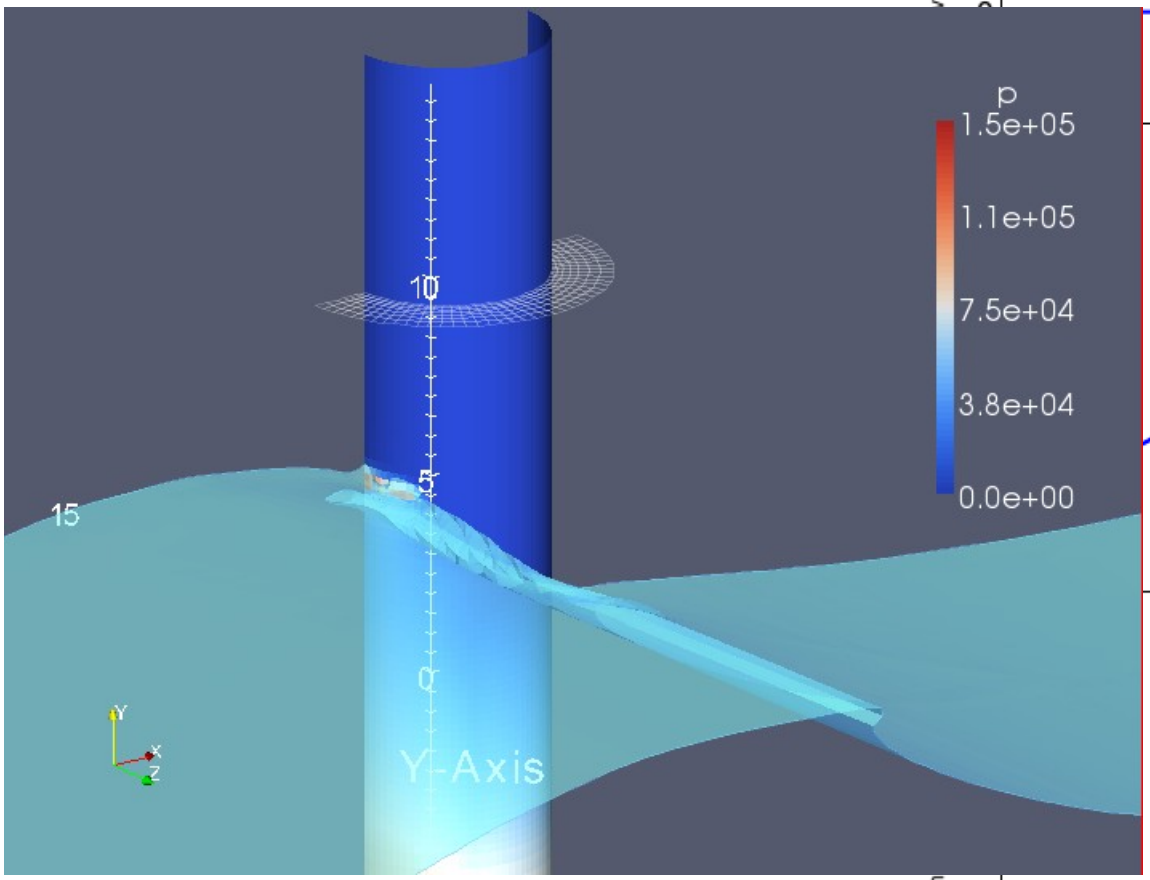
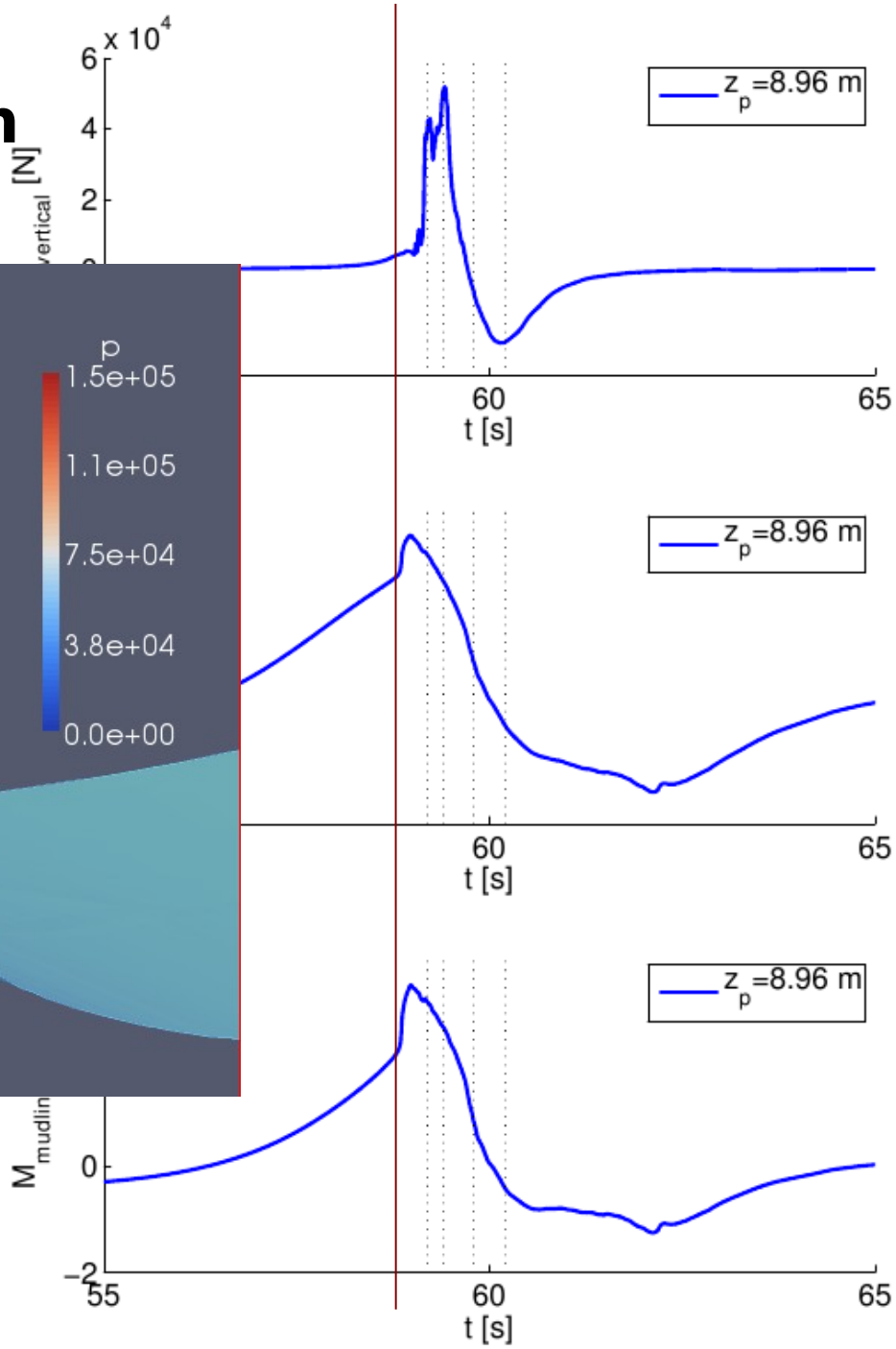
Platform height of 8.96m





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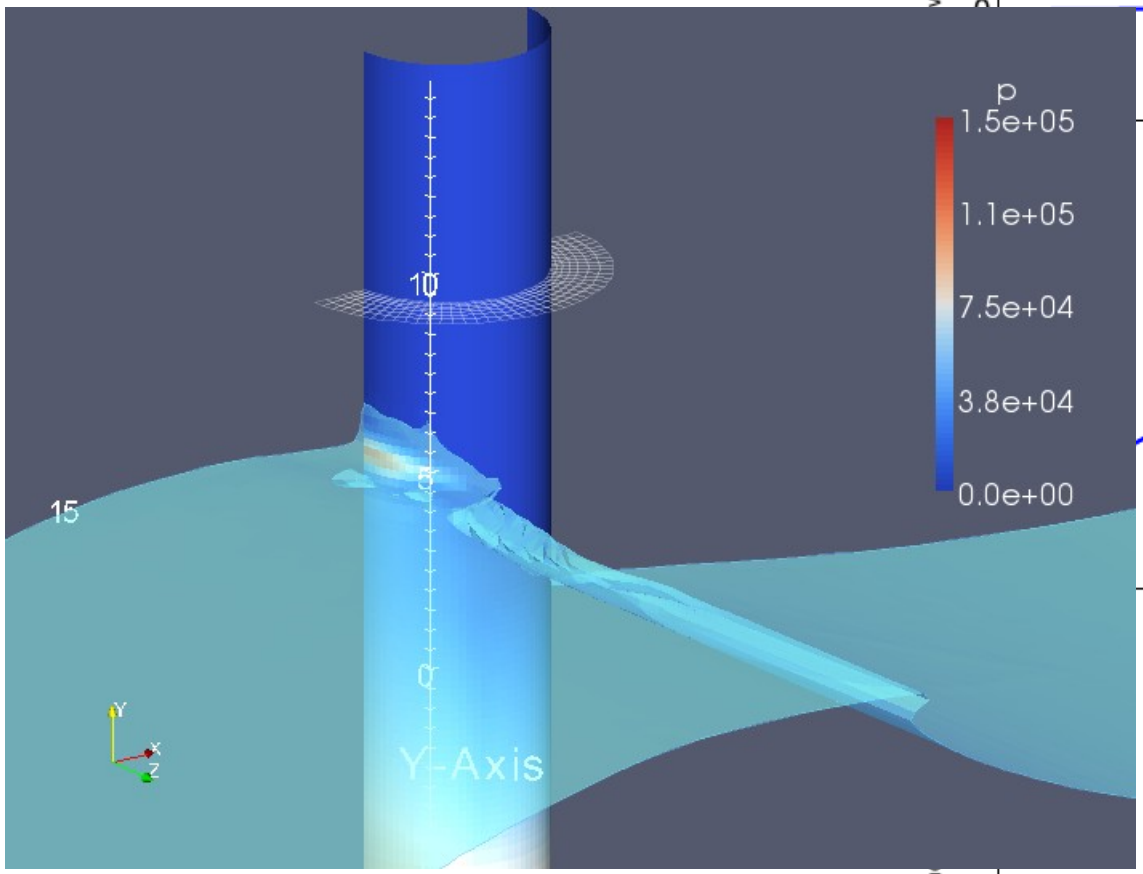

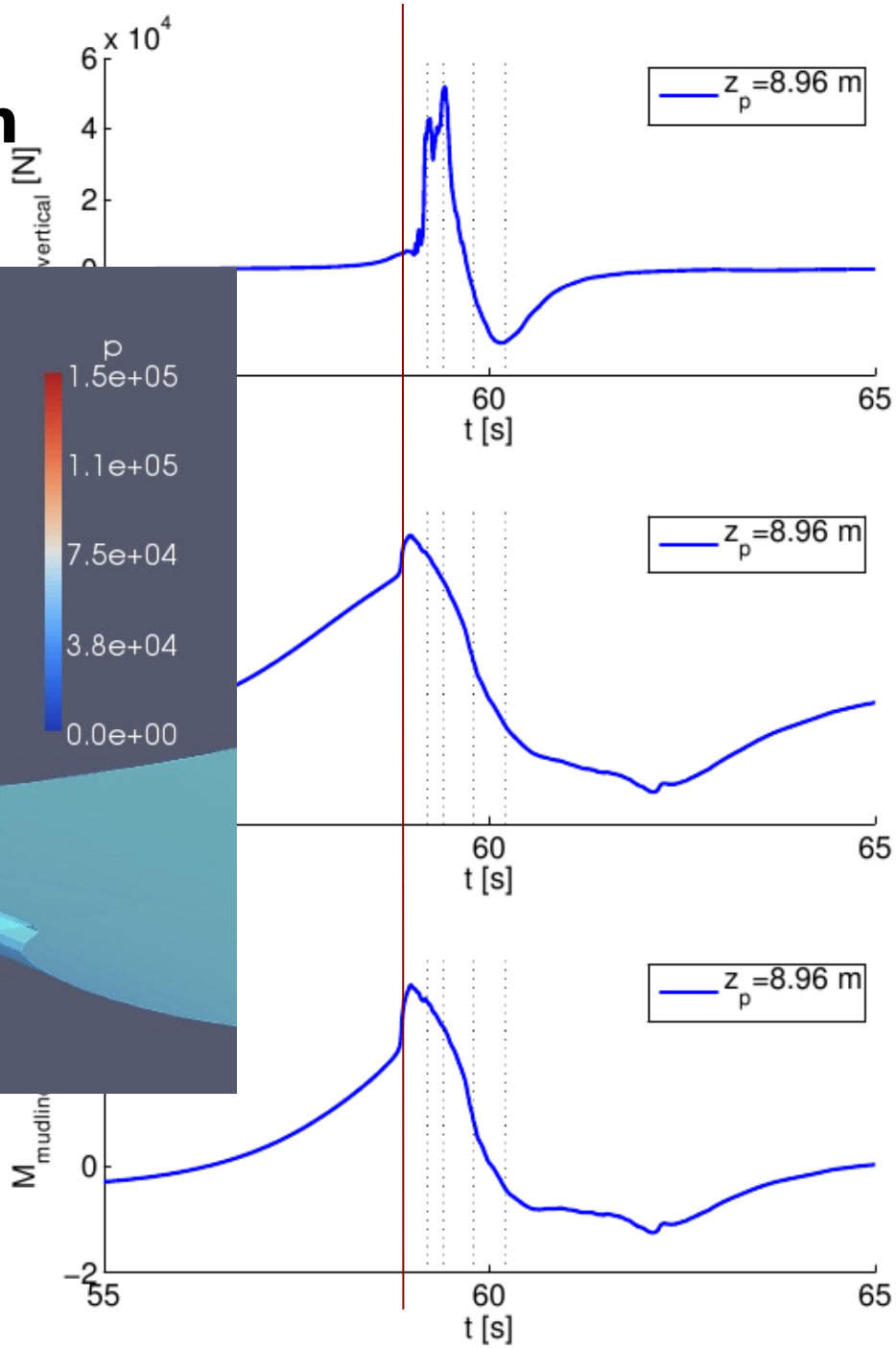

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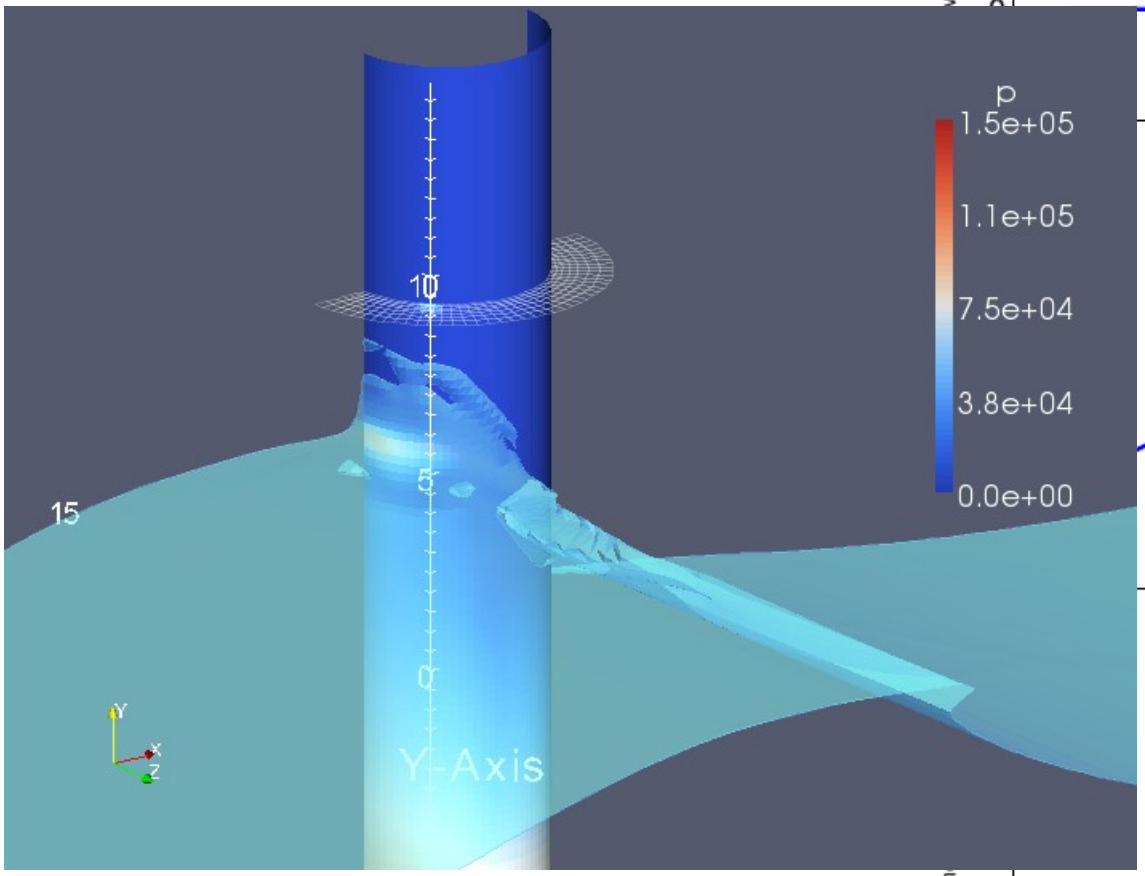

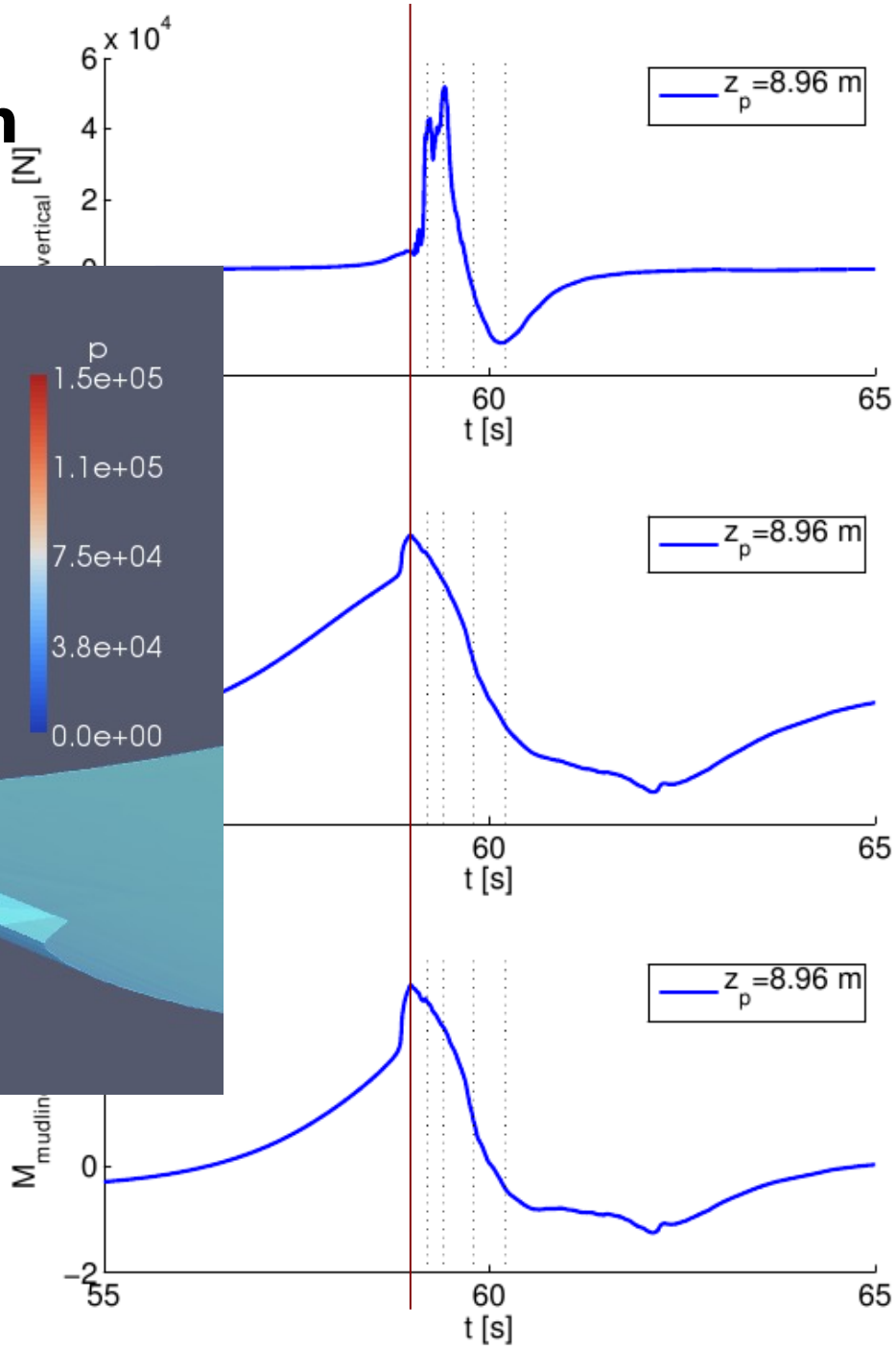

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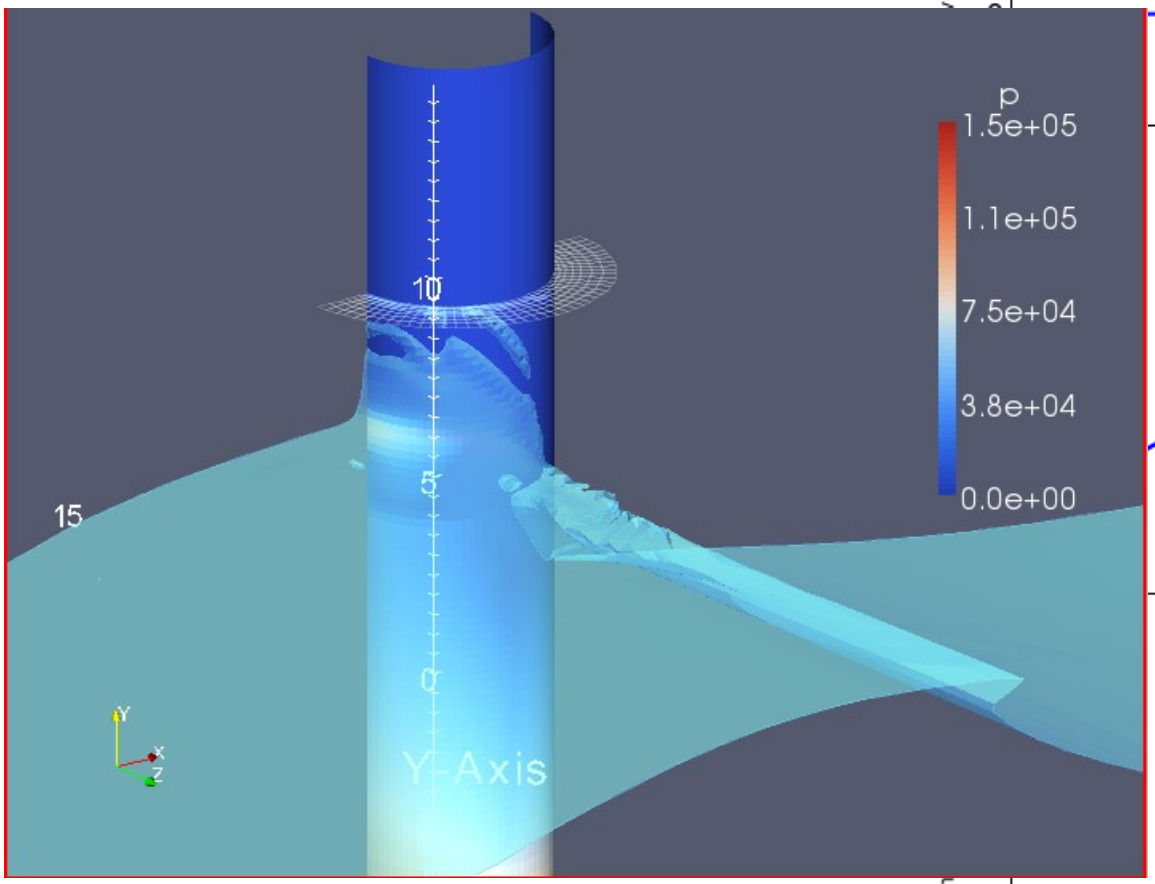

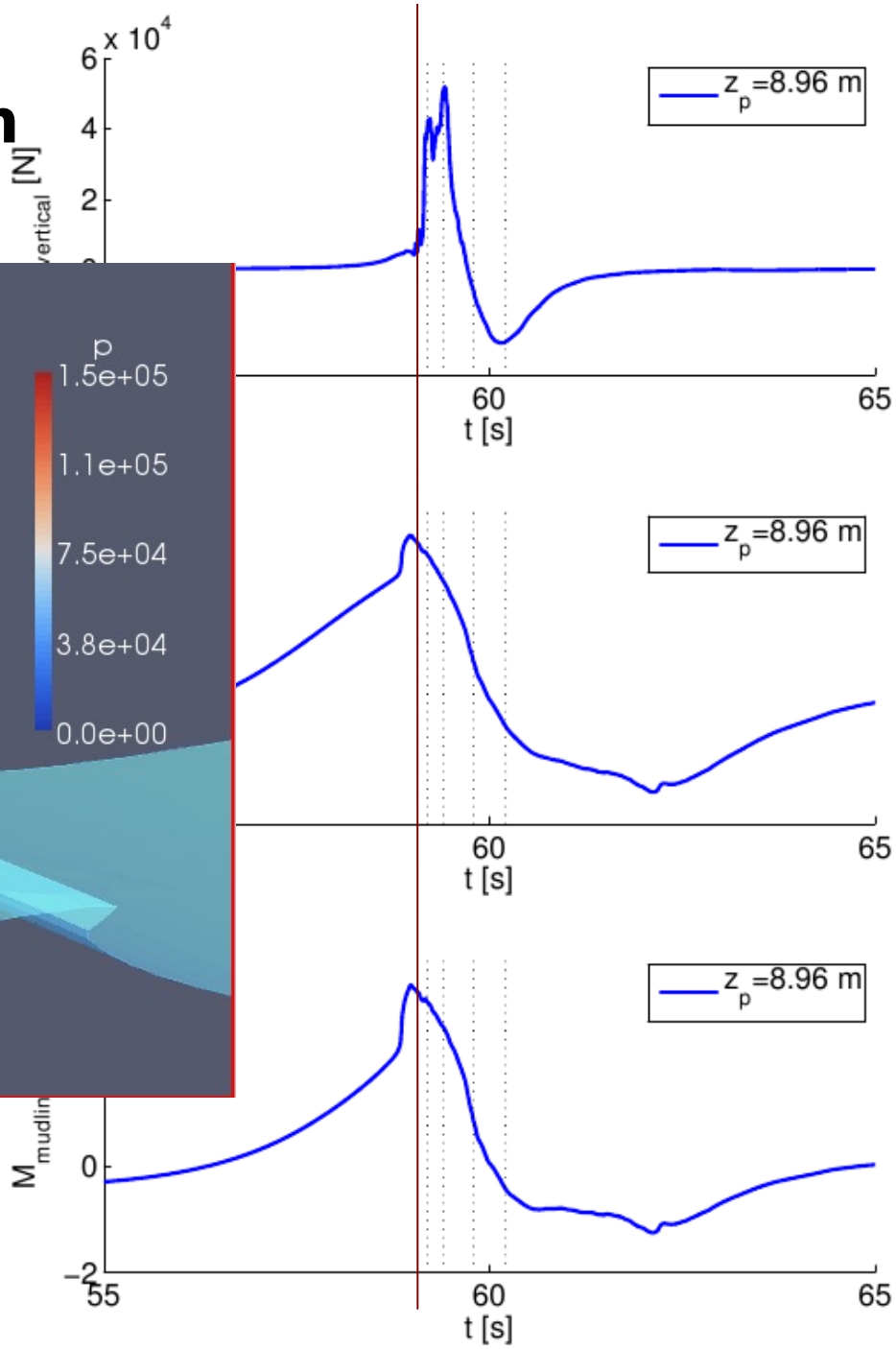

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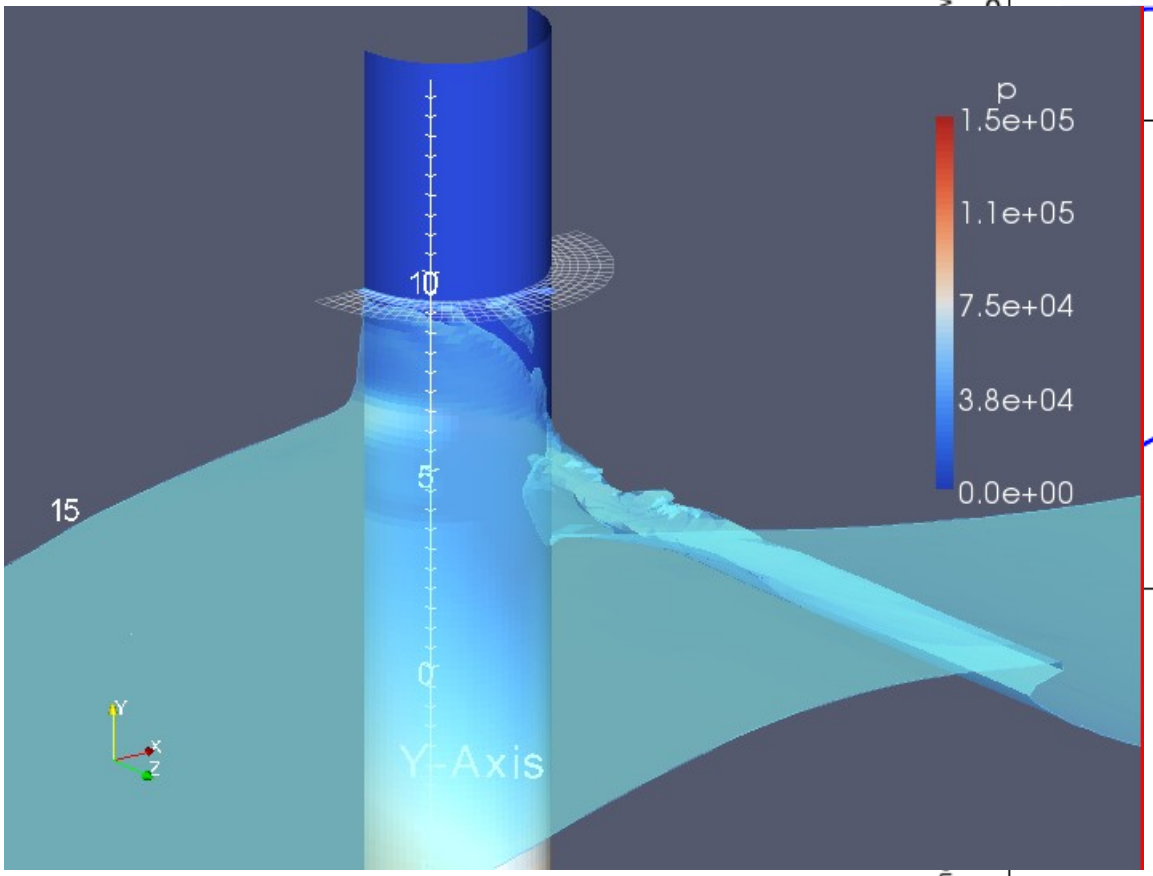
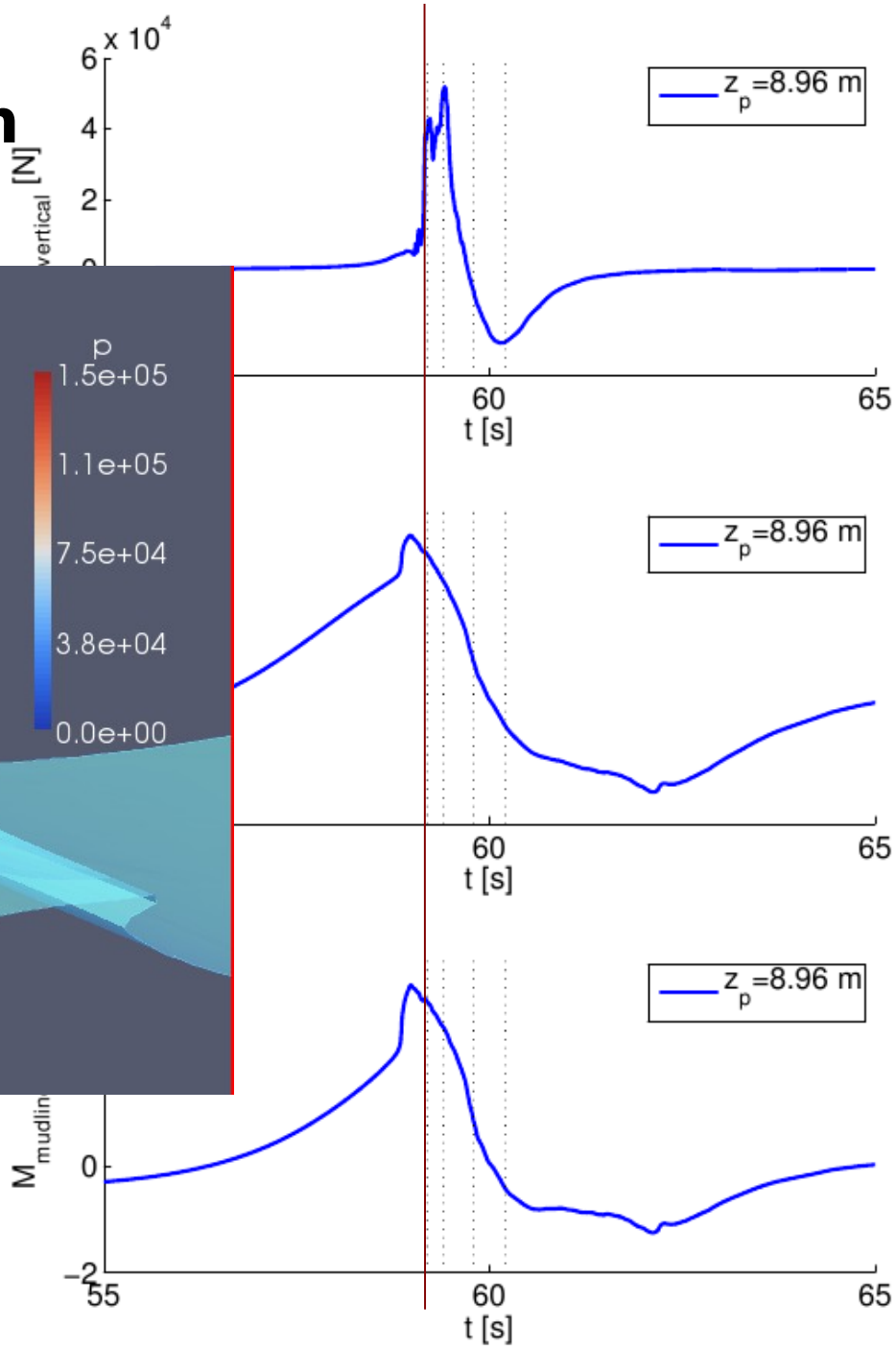
Platform height of 8.96m





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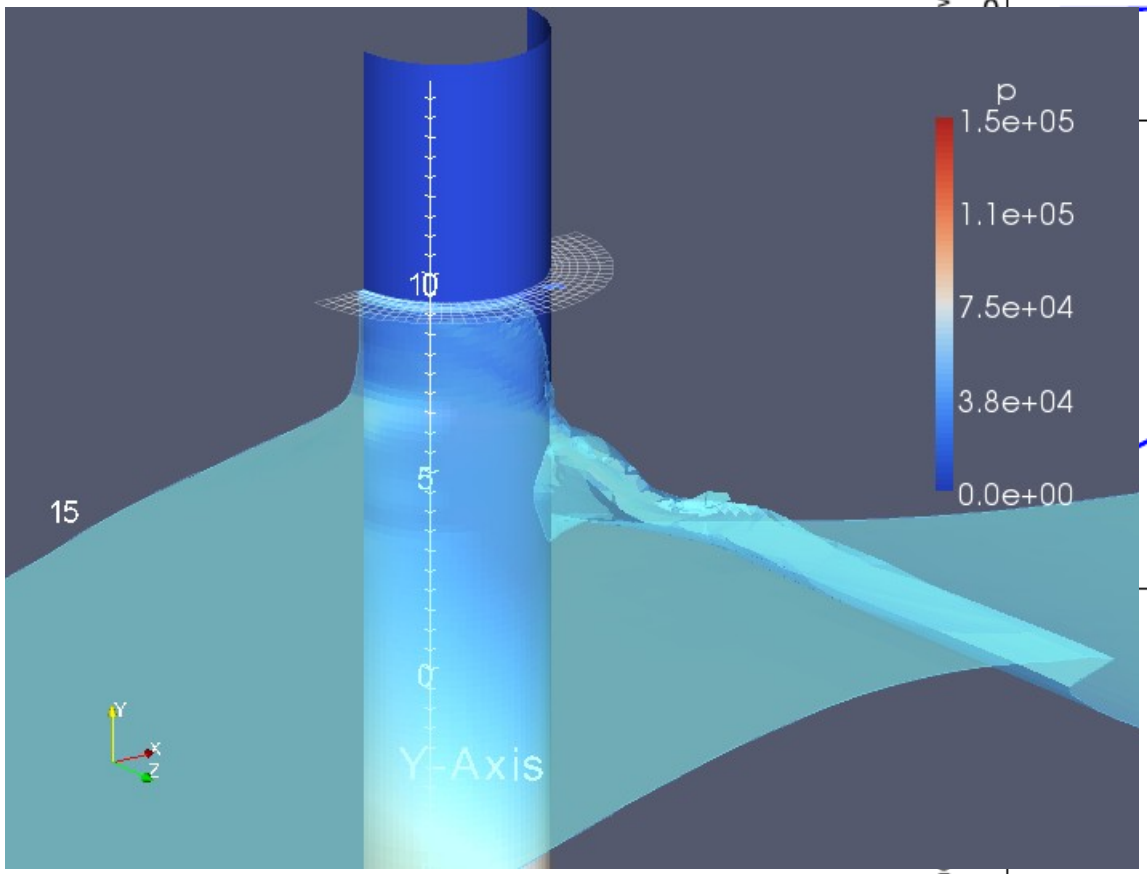
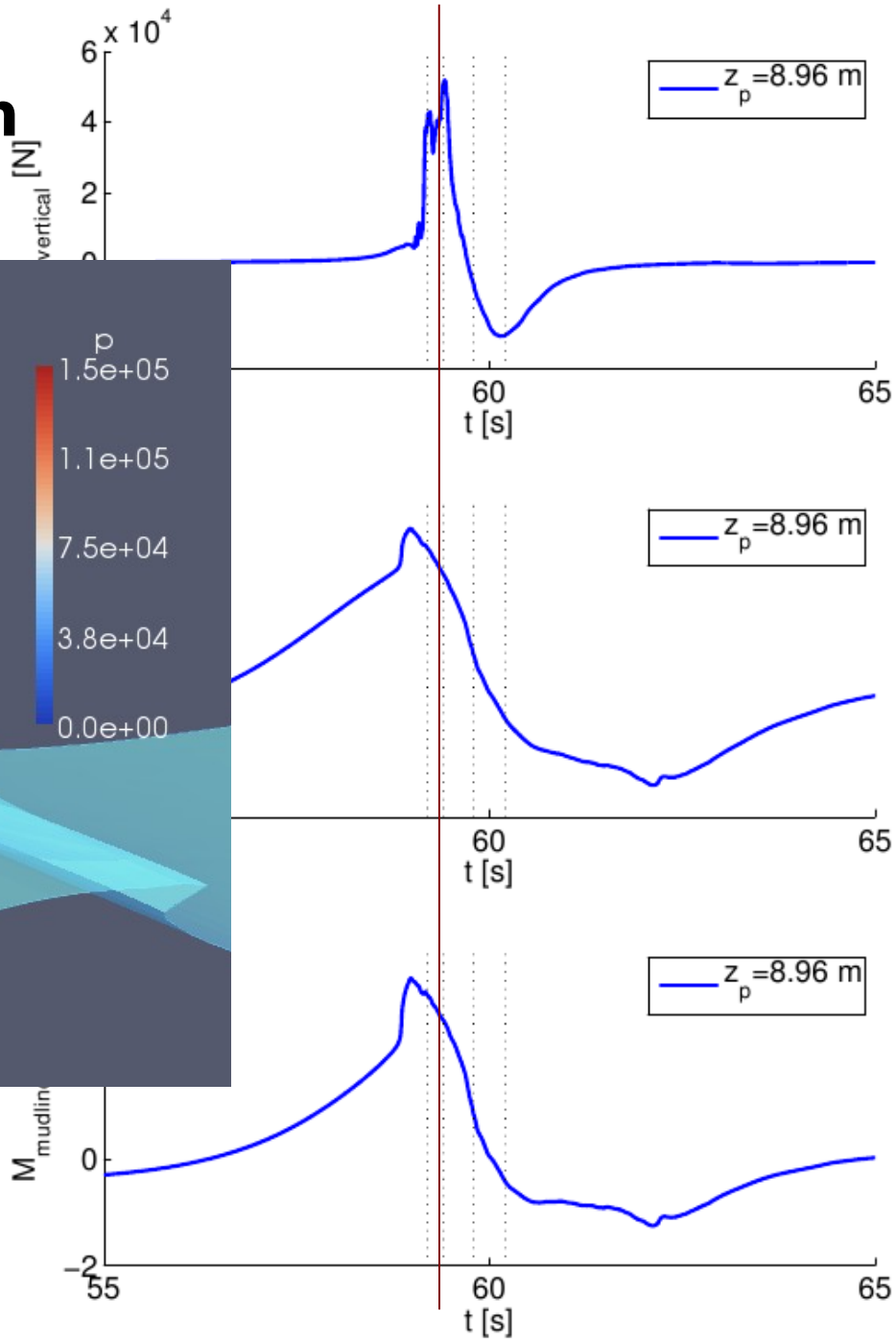
Platform height of 8.96m





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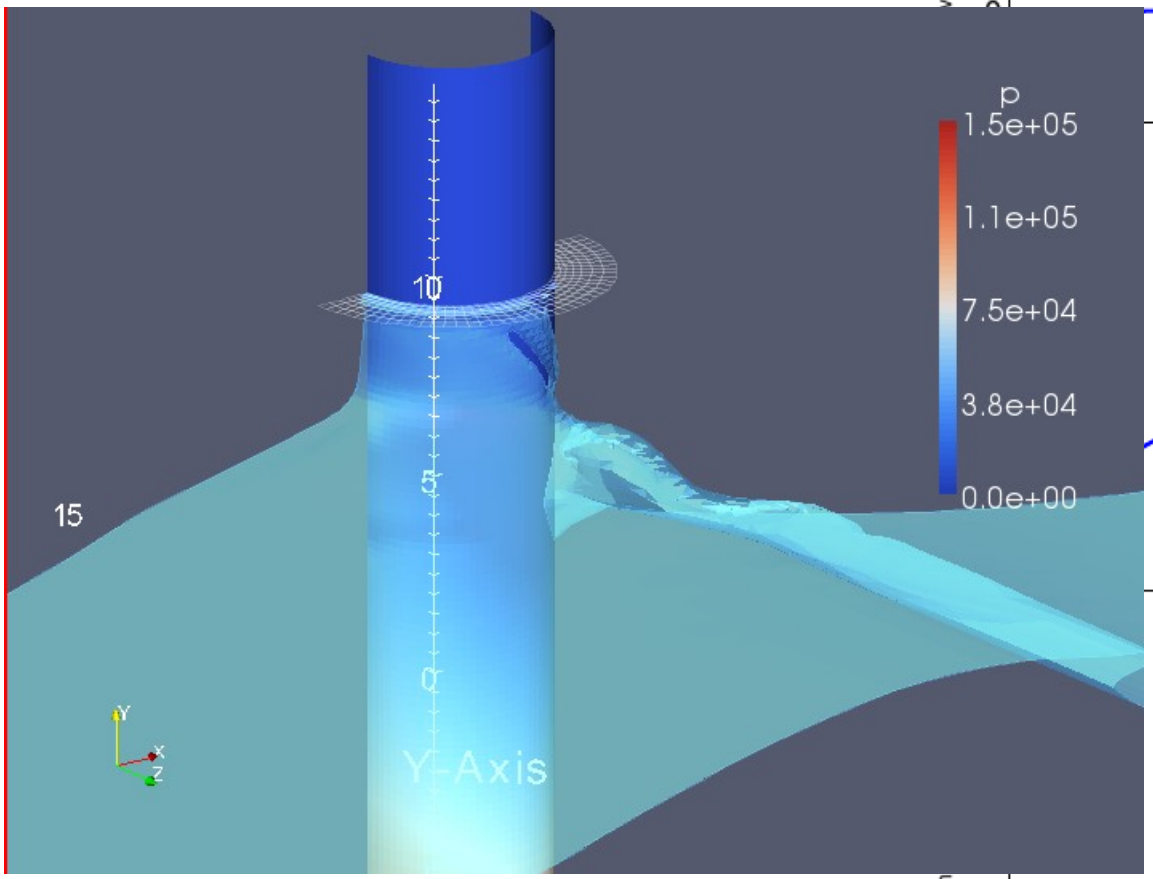

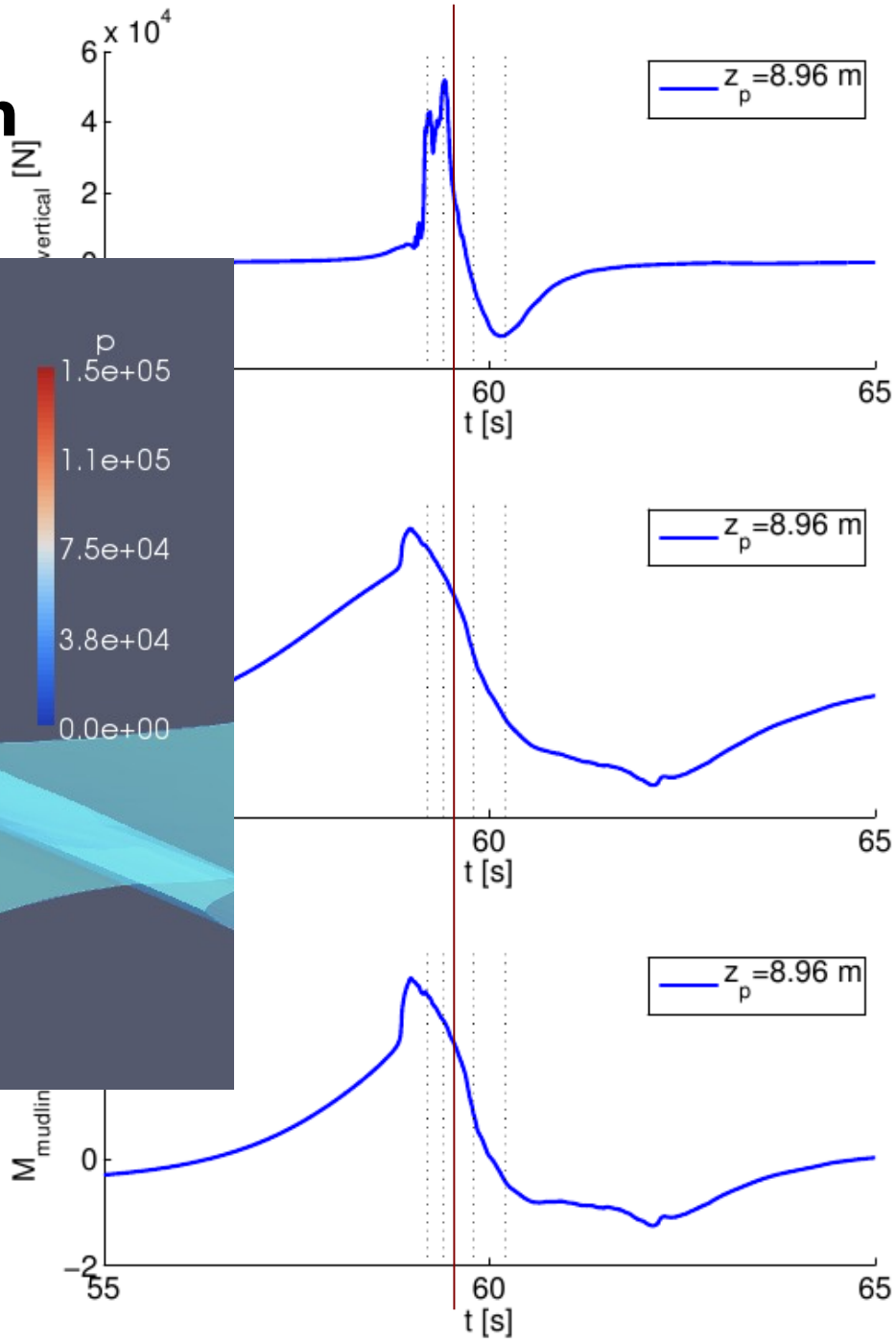

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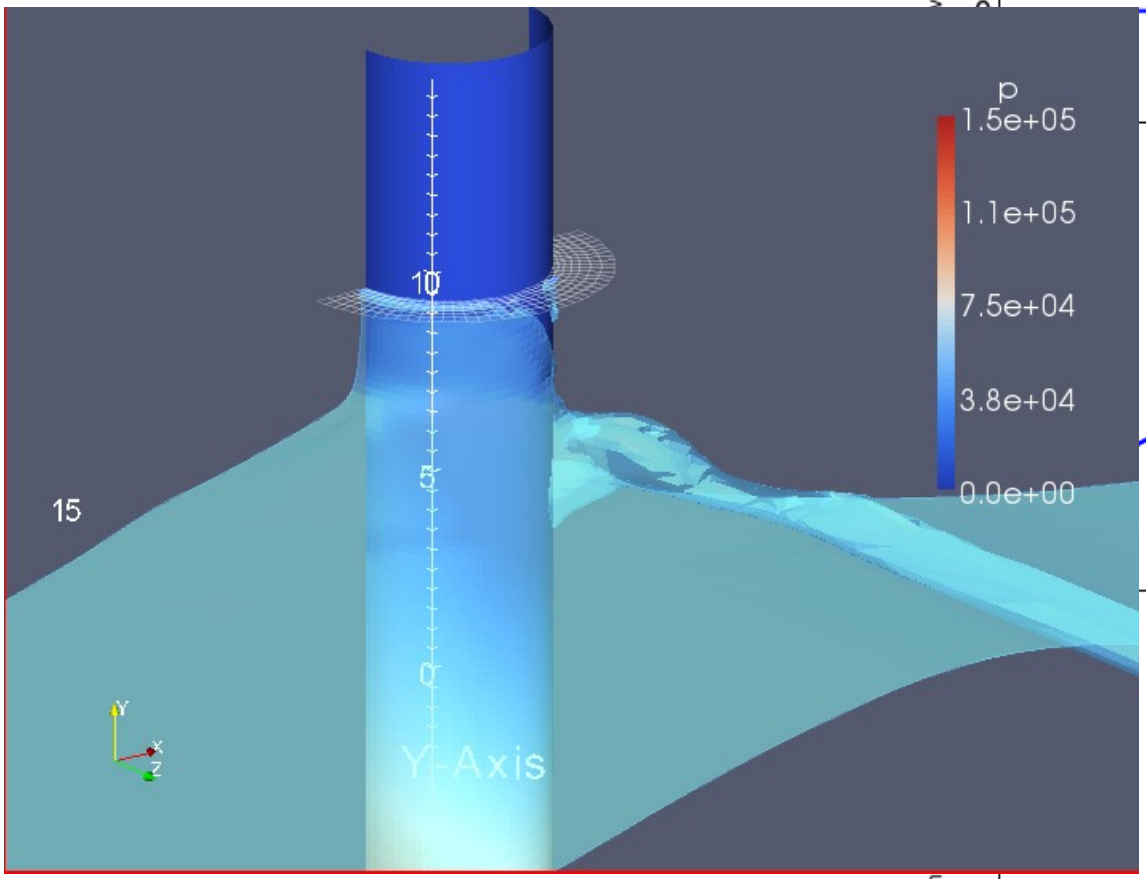
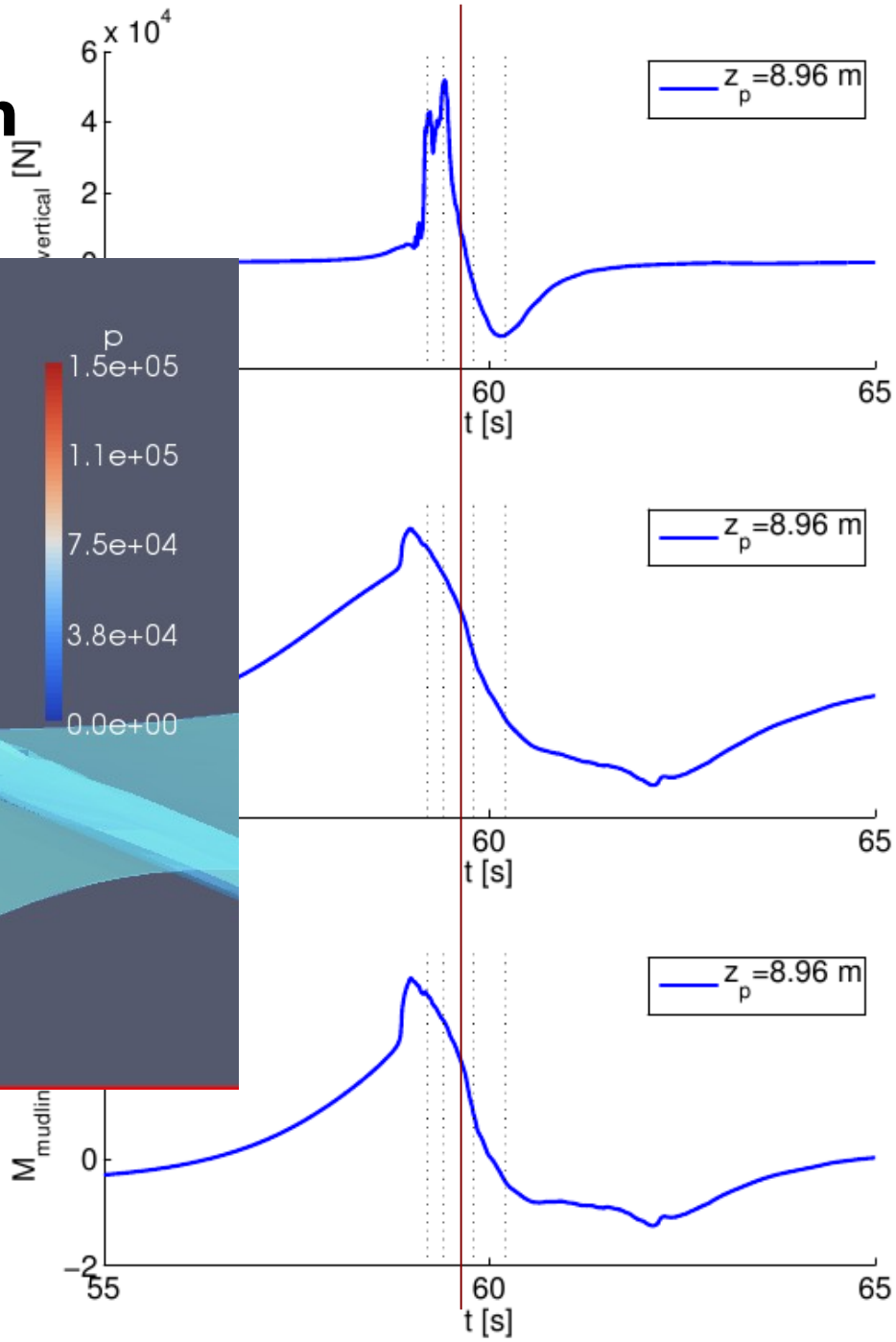
Platform height of 8.96m





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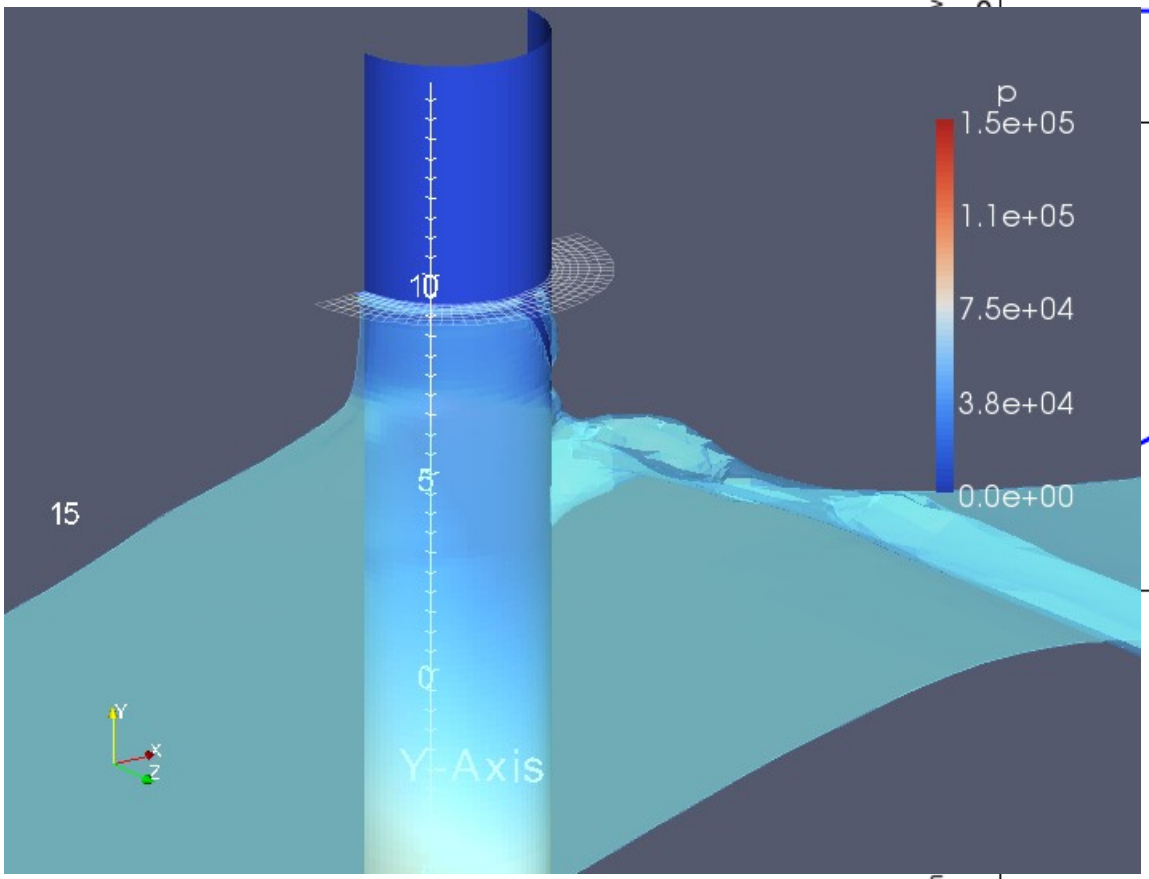

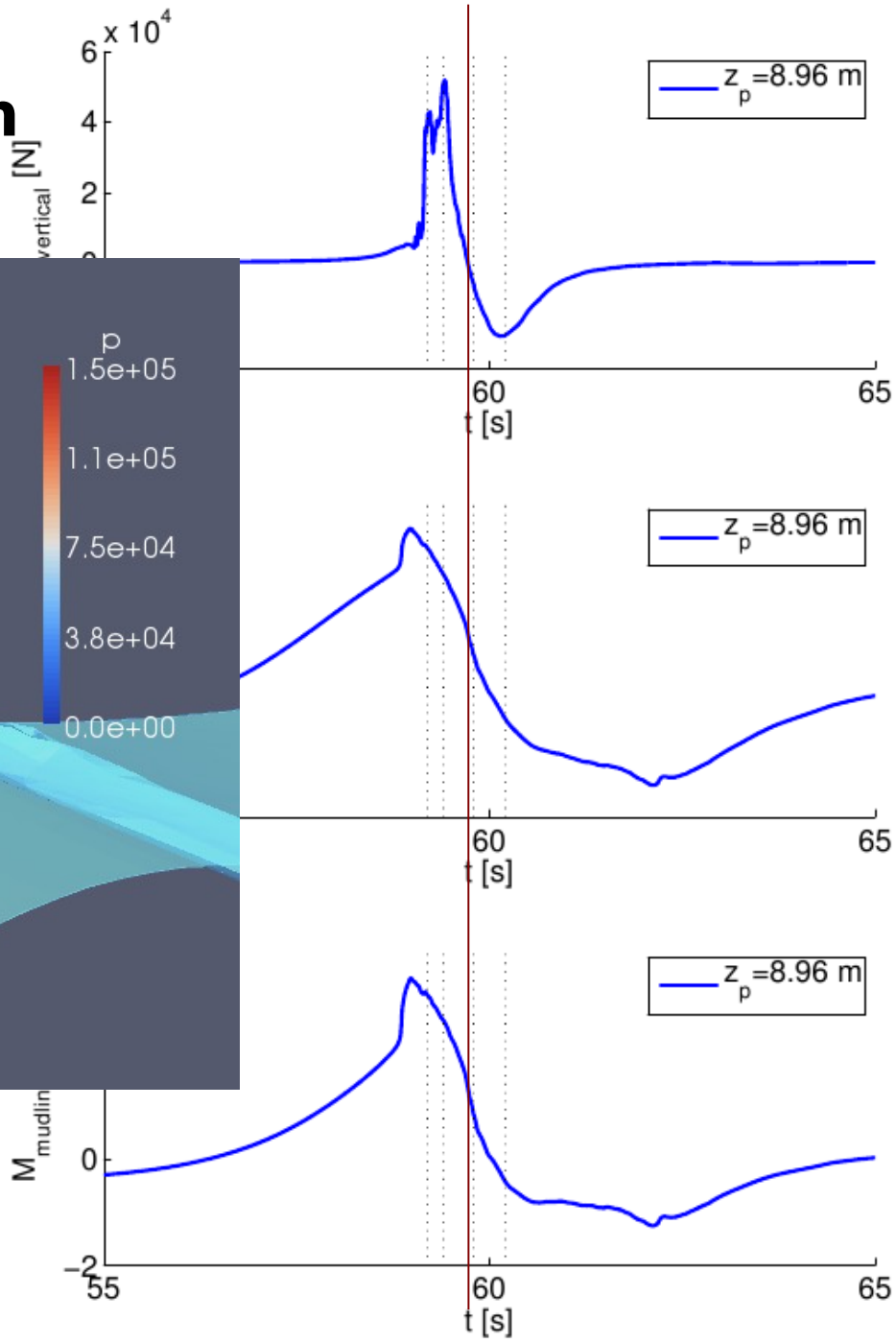

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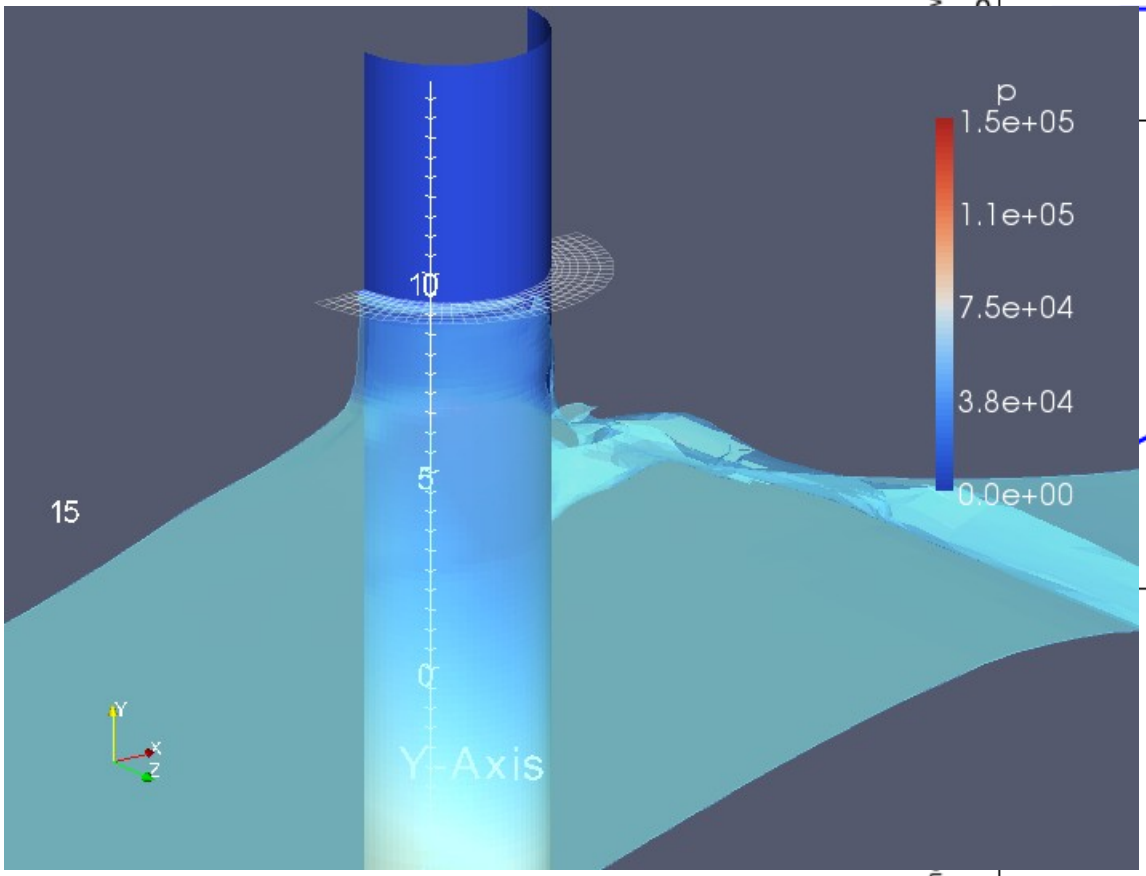
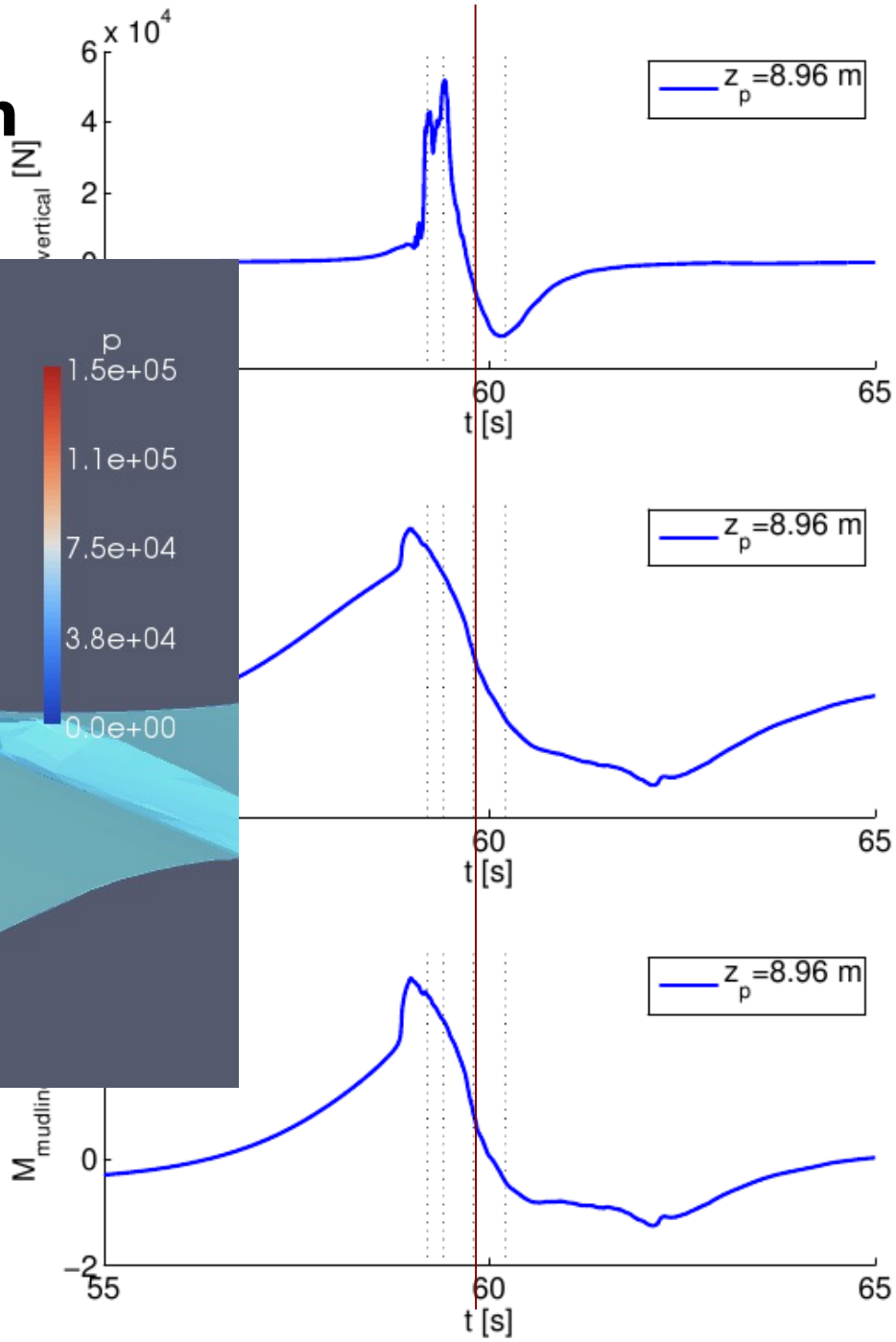
Platform height of 8.96m





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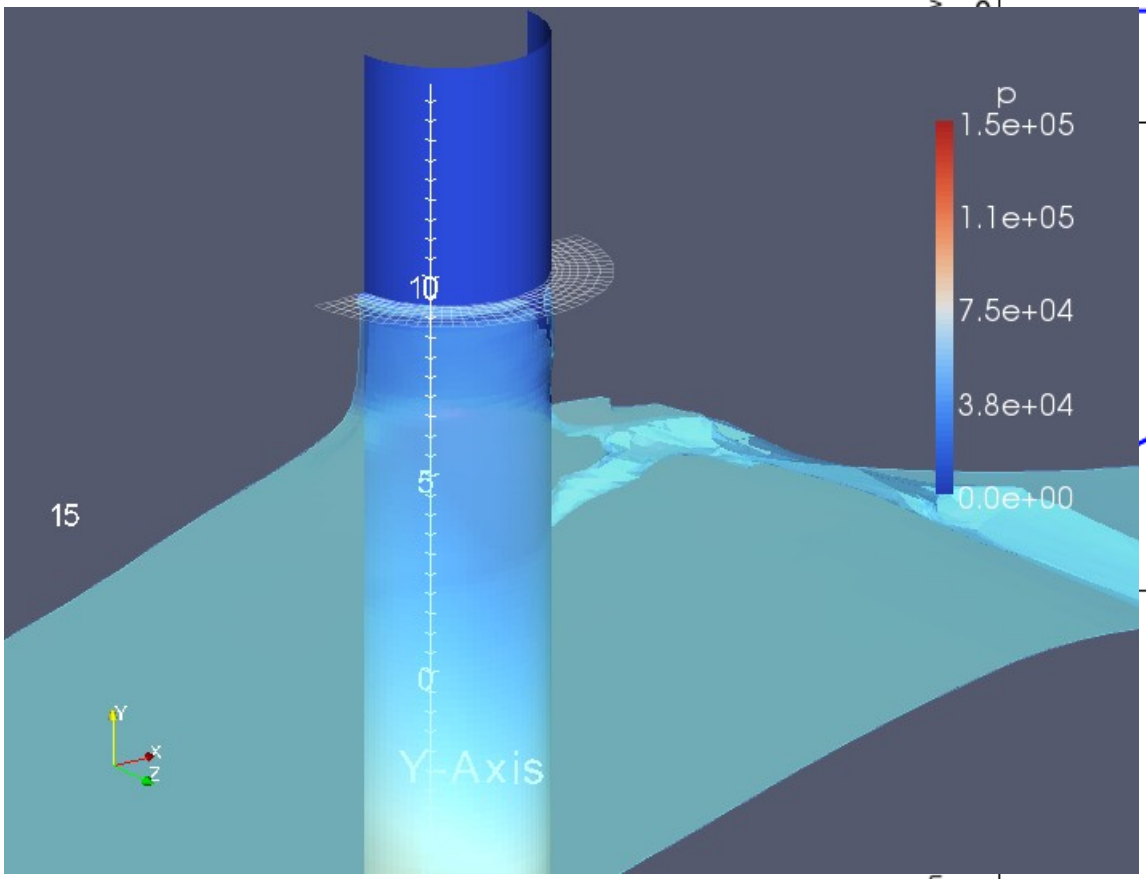

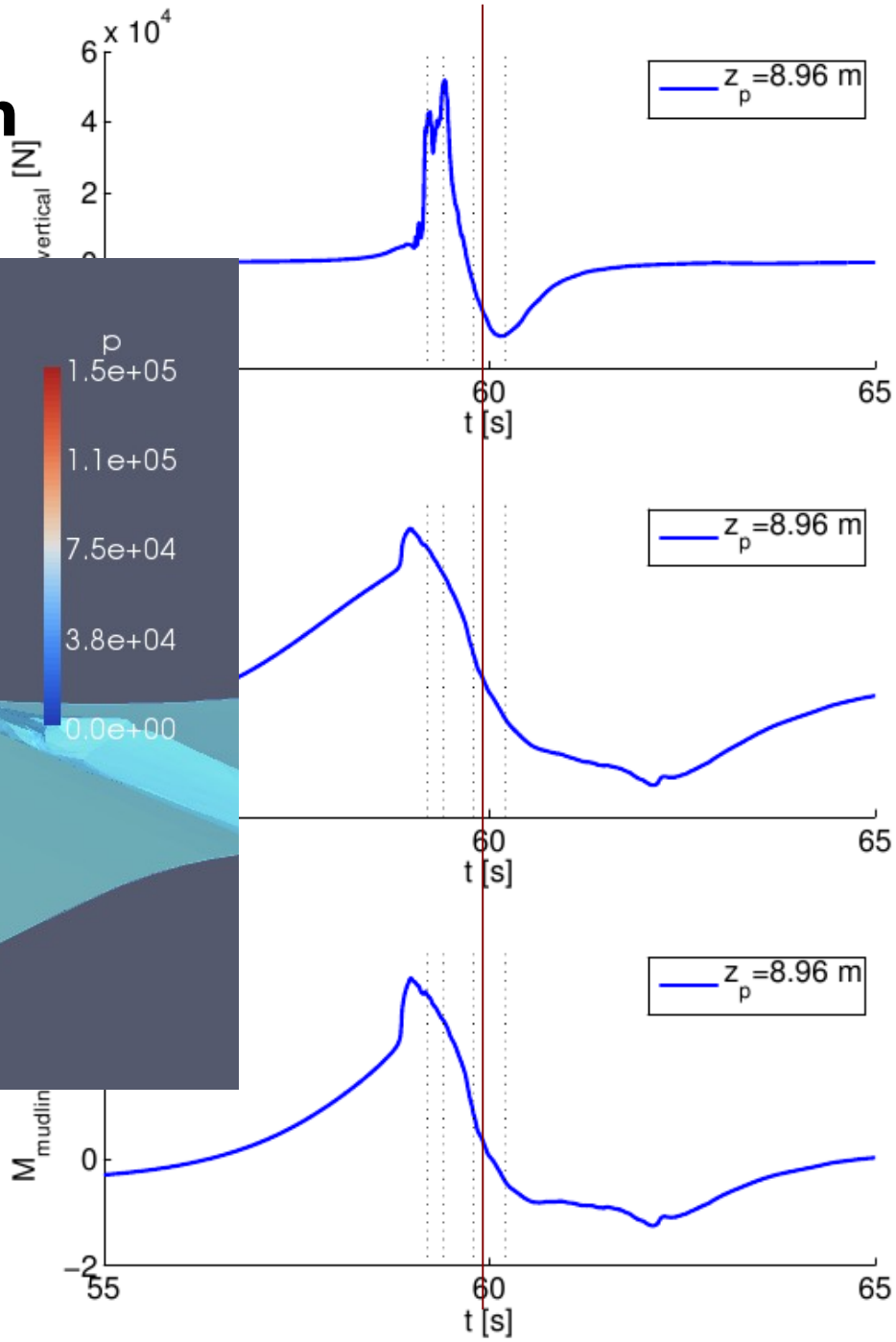

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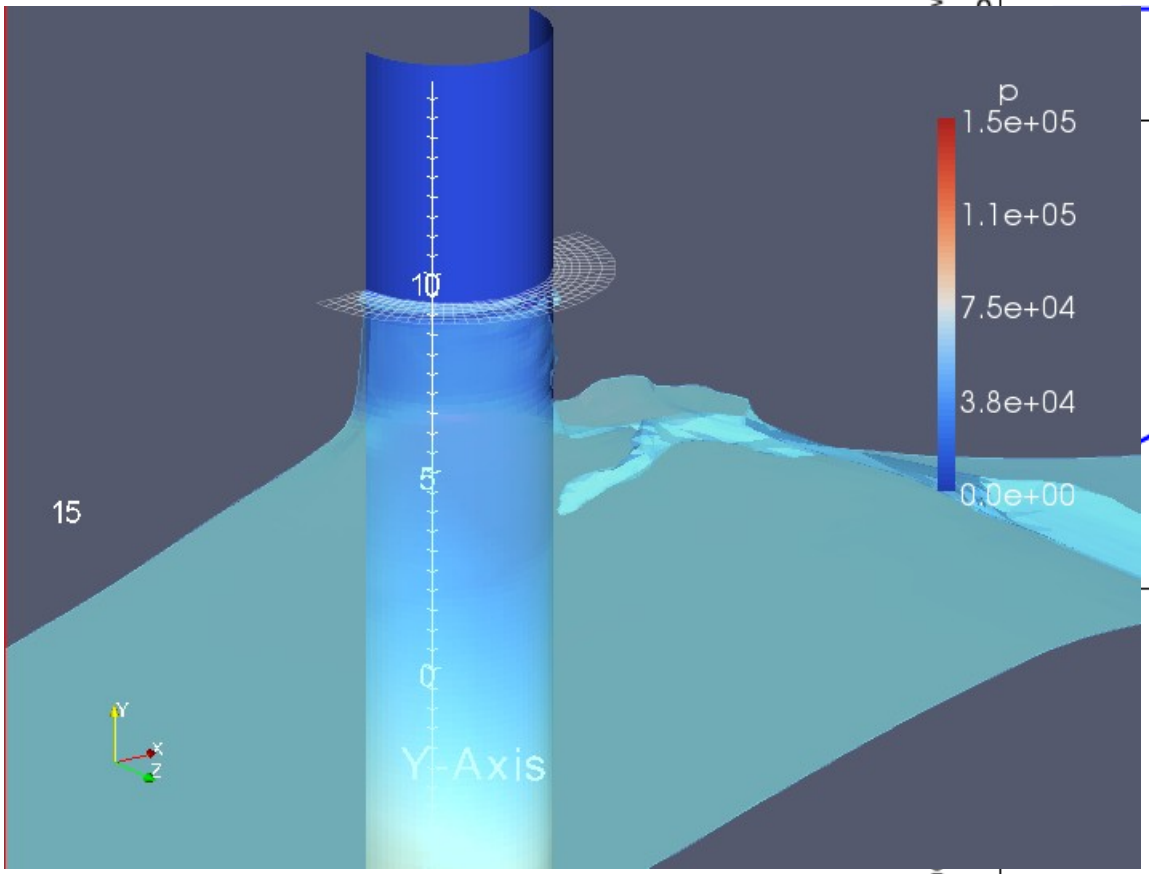

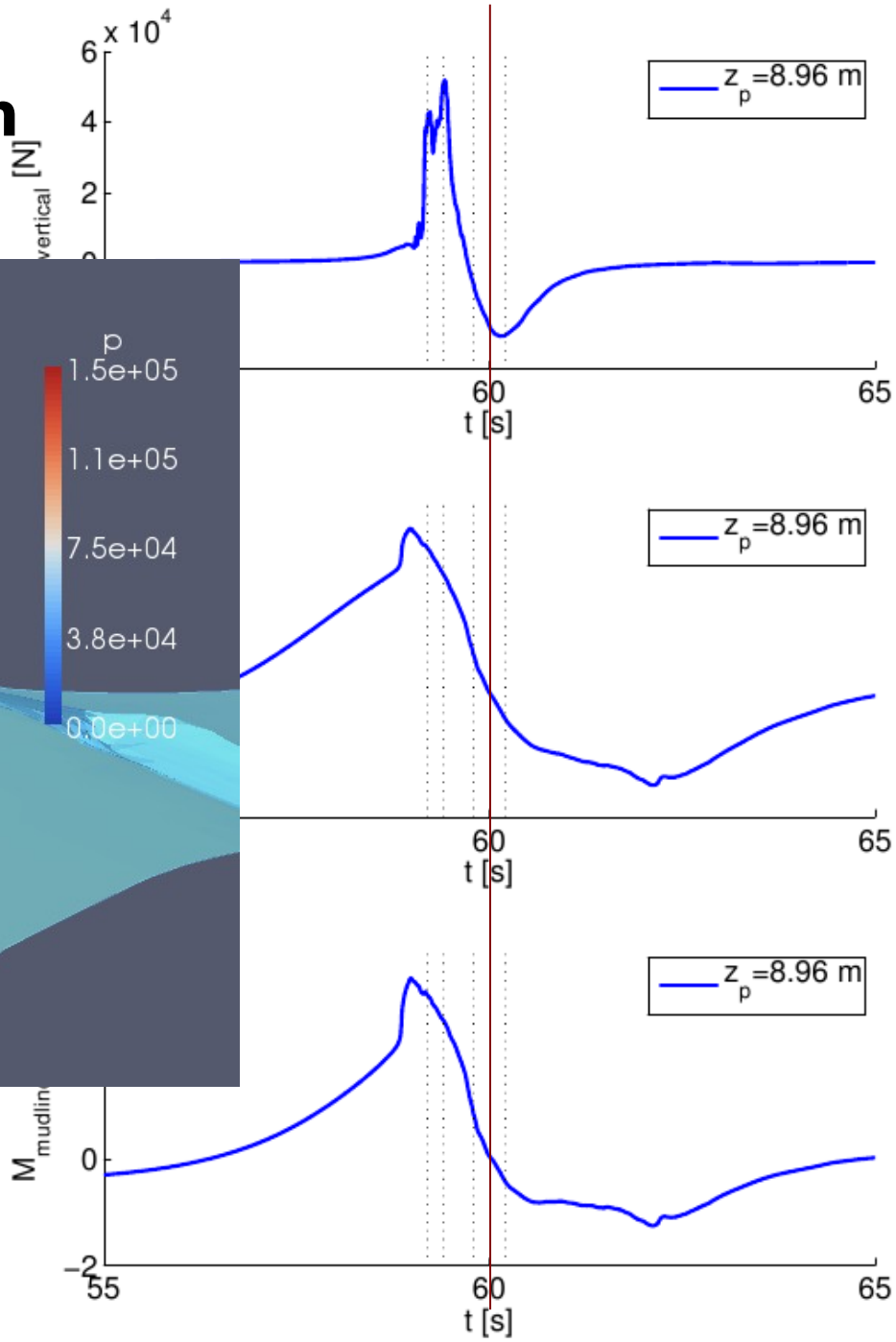

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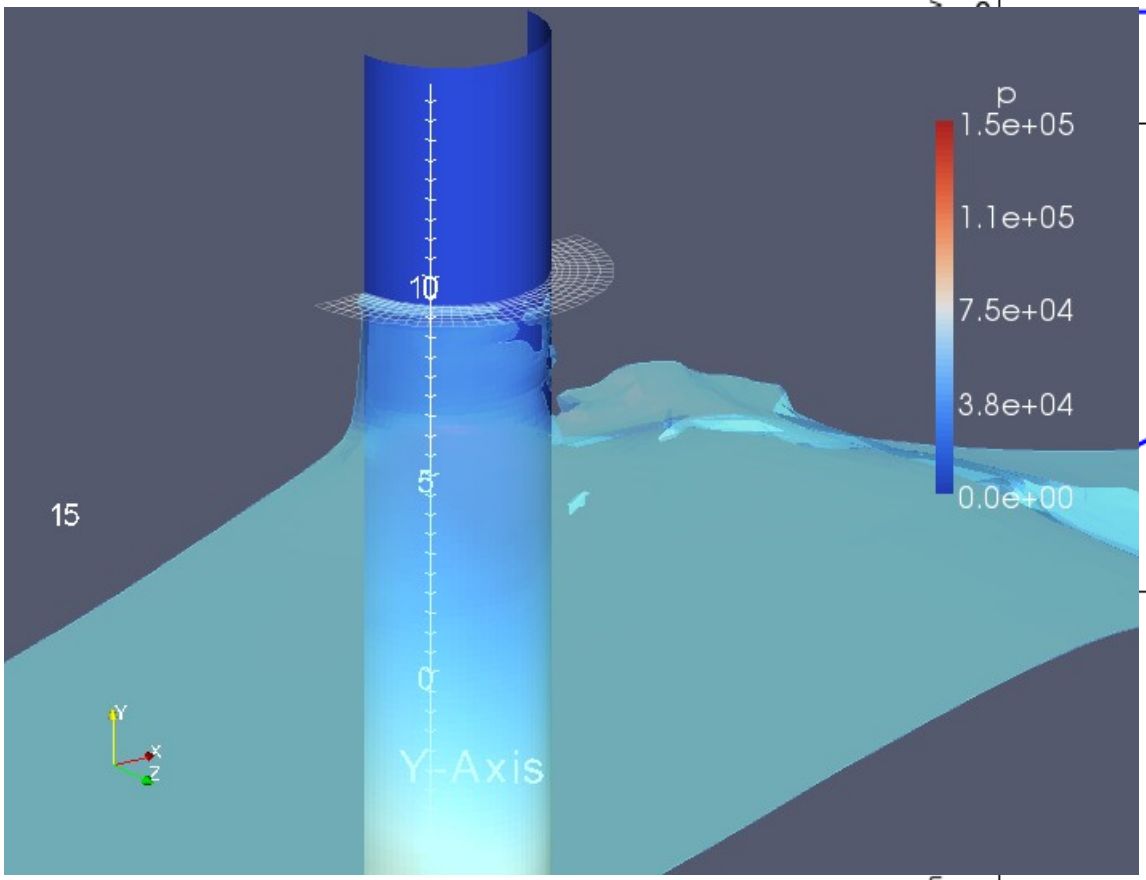

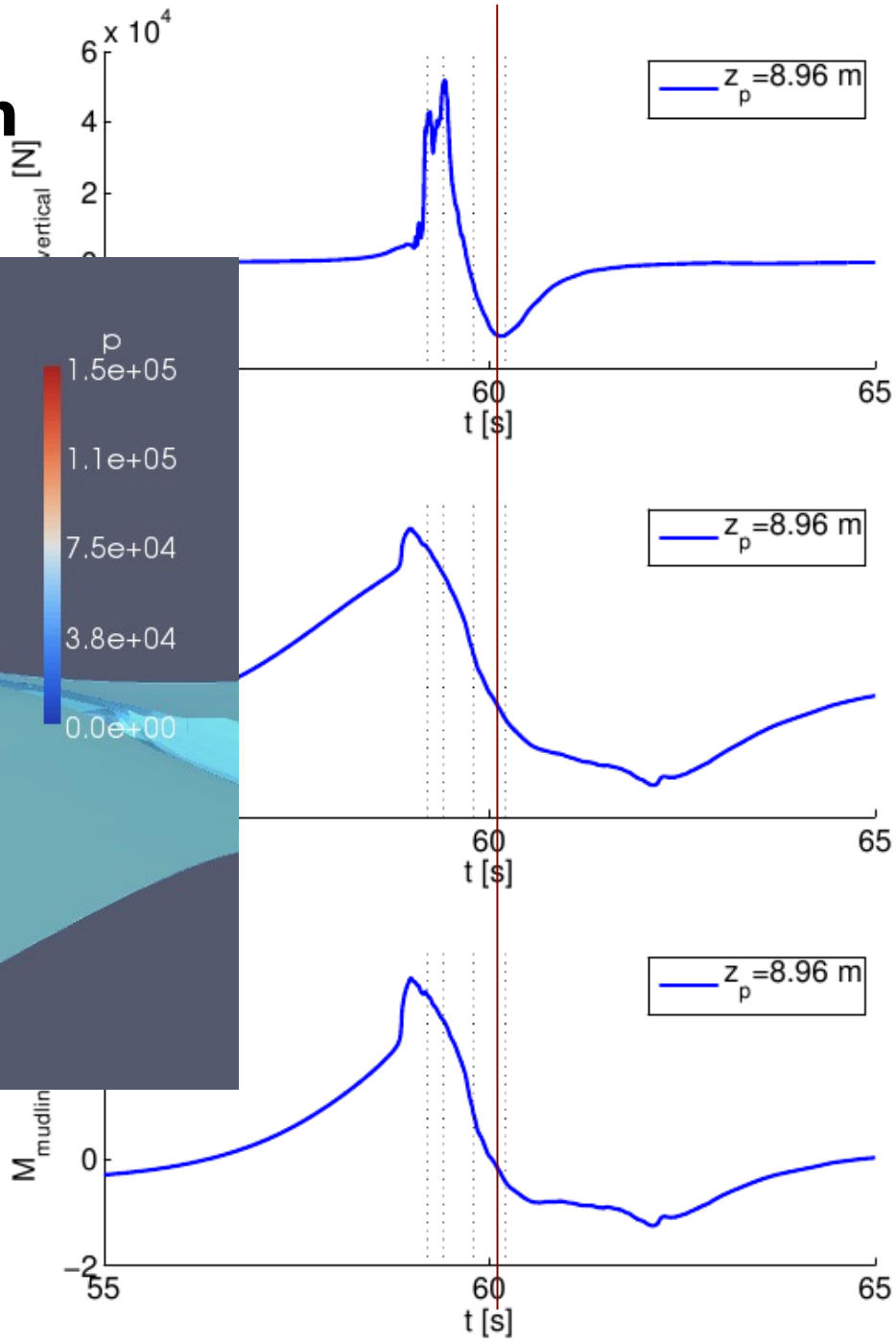

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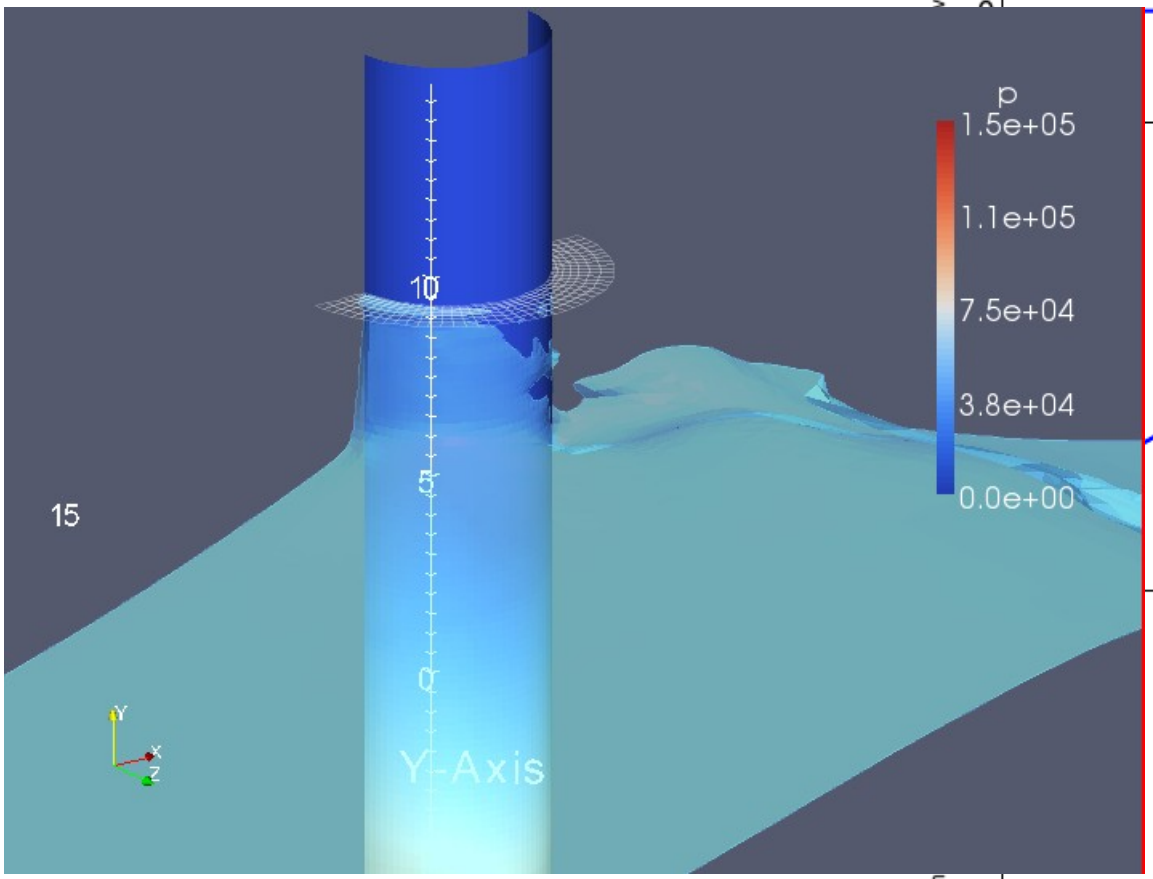

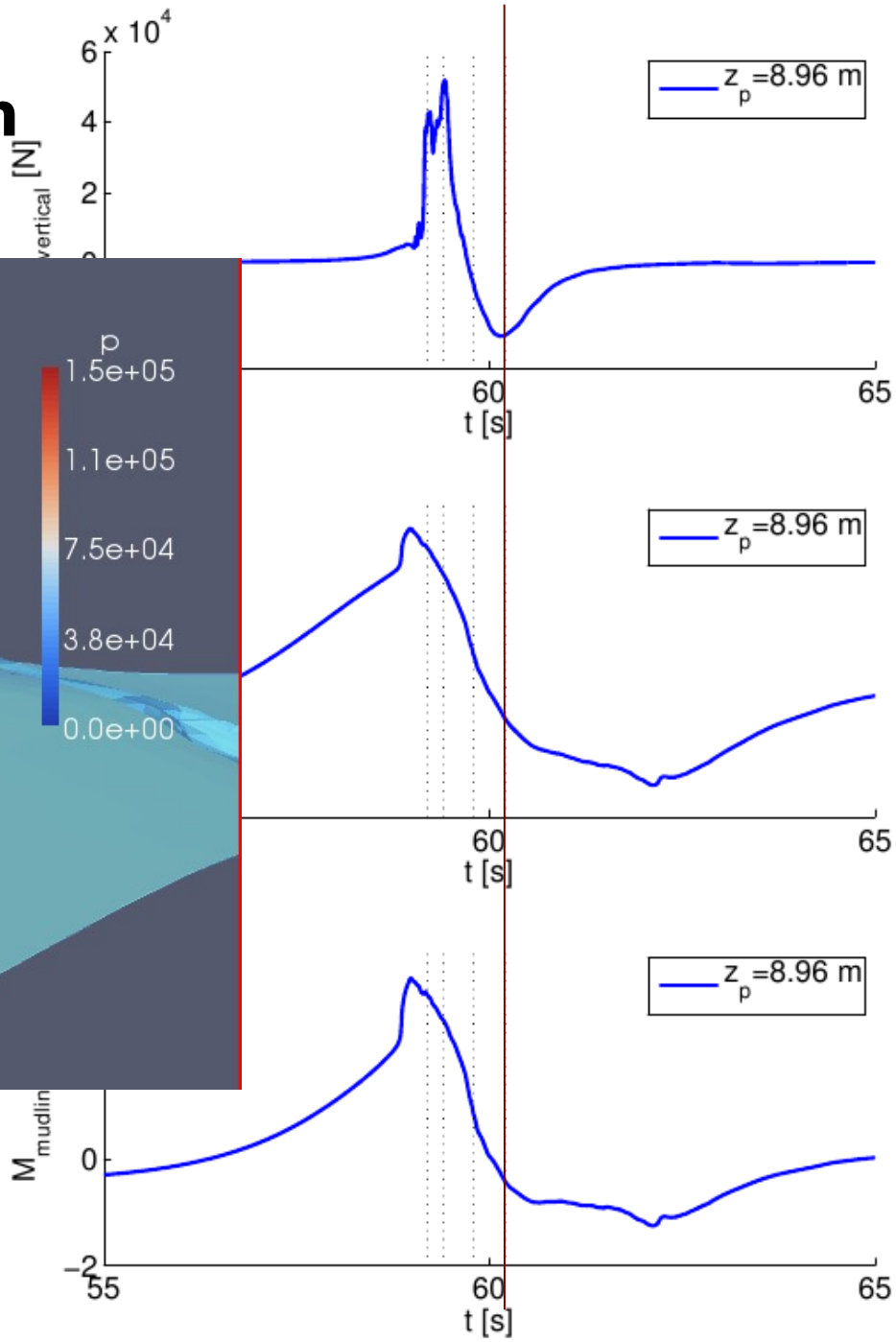

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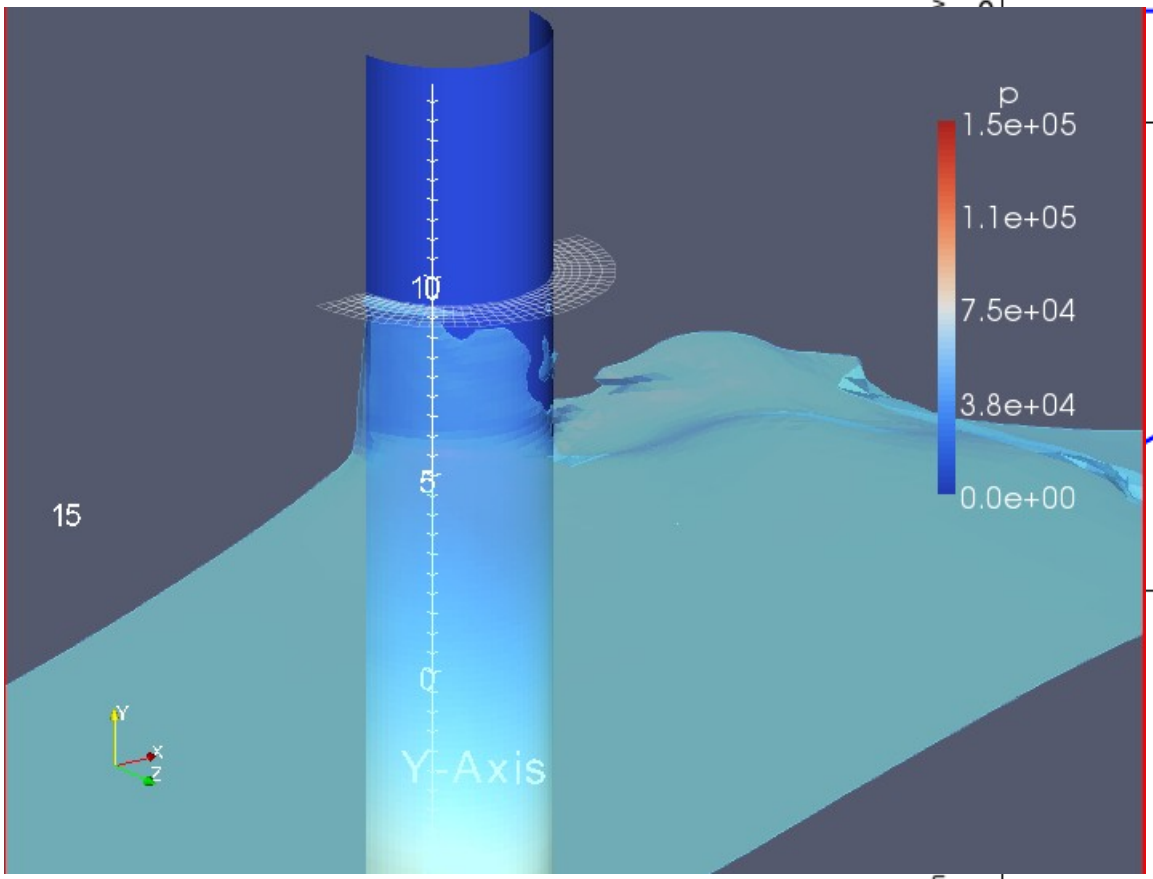

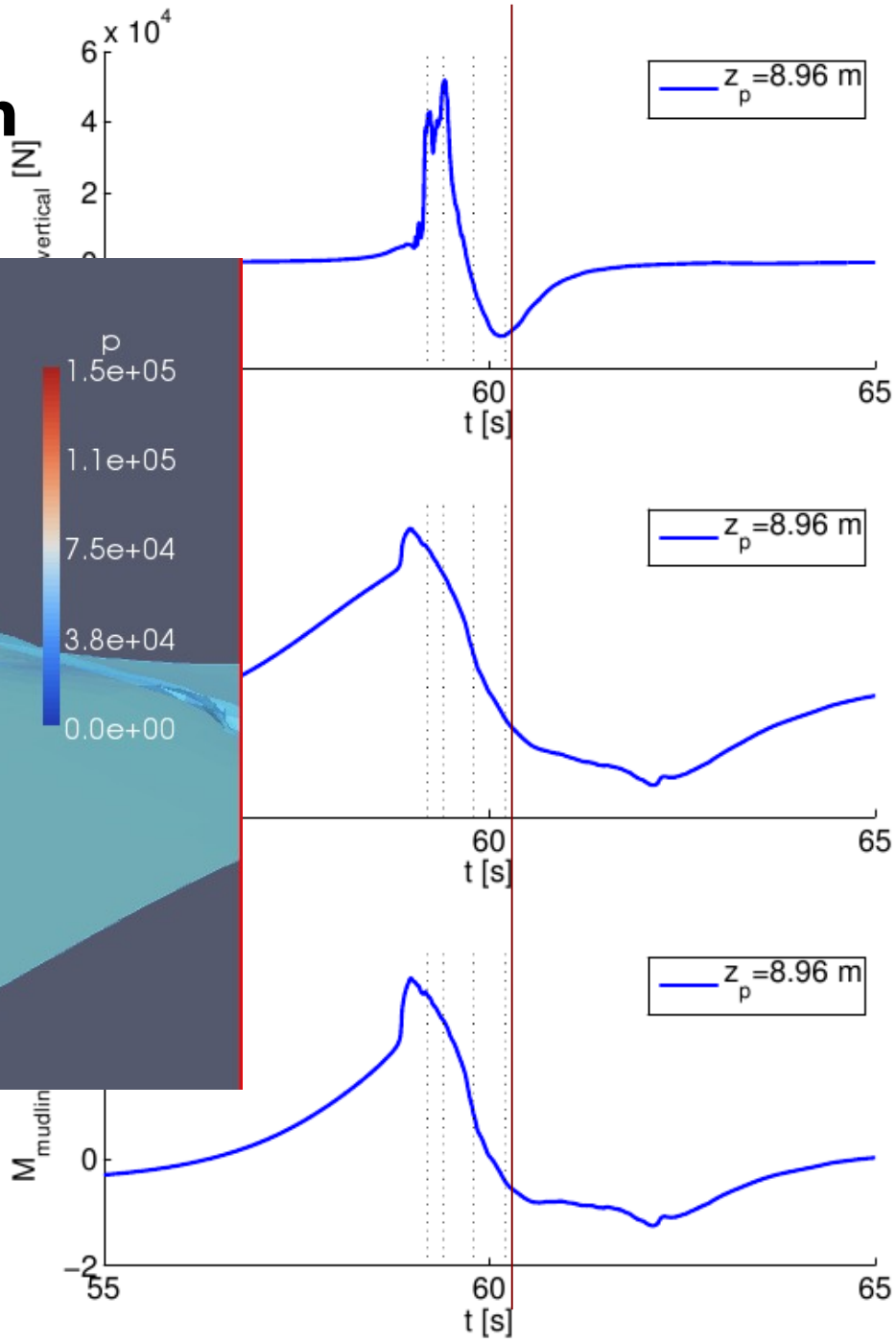

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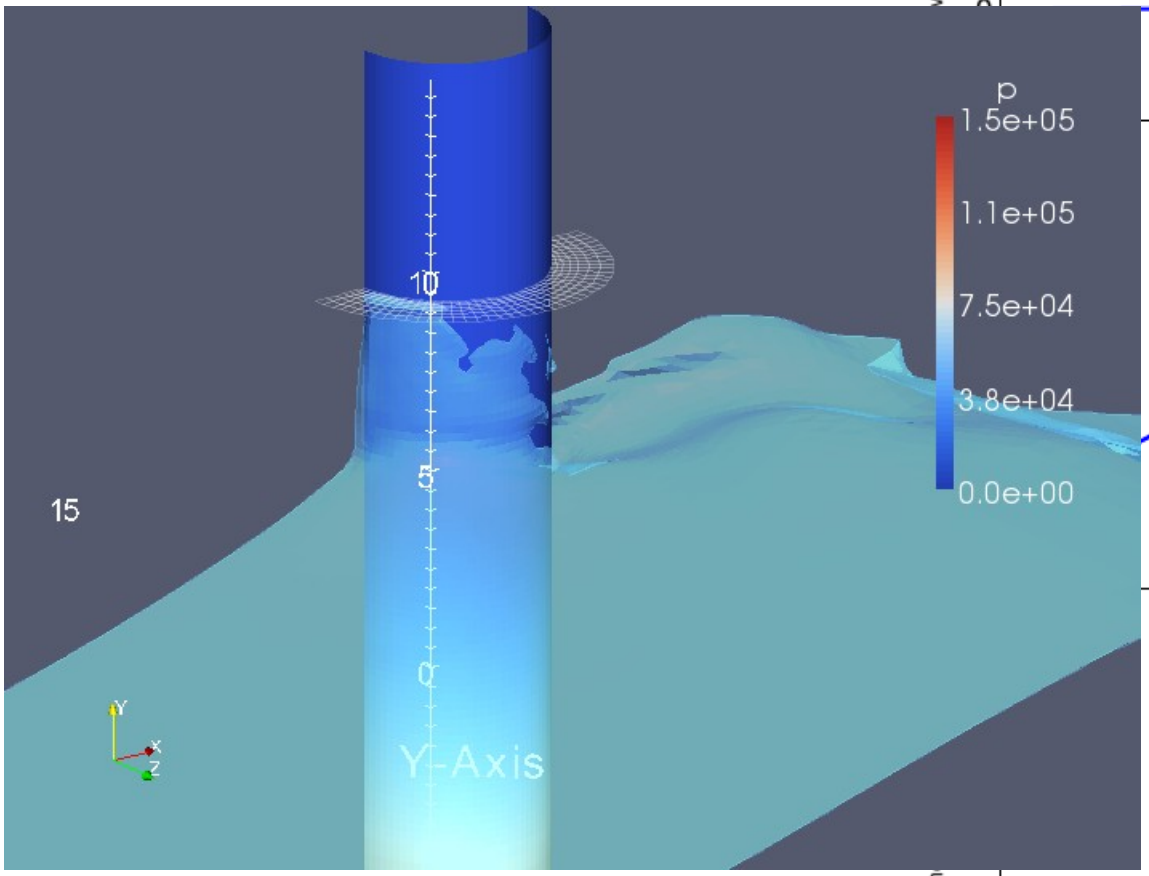
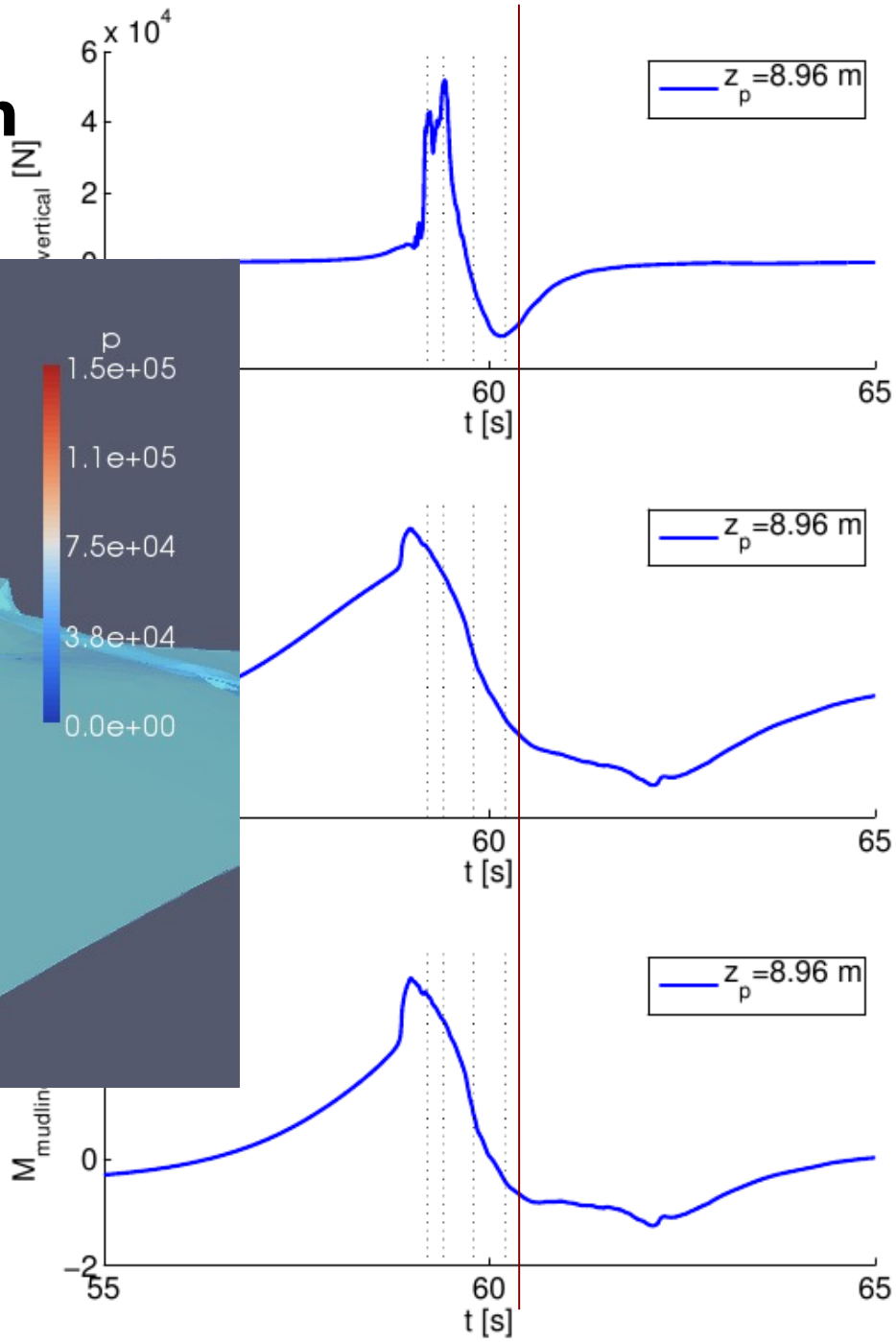
Platform height of 8.96m





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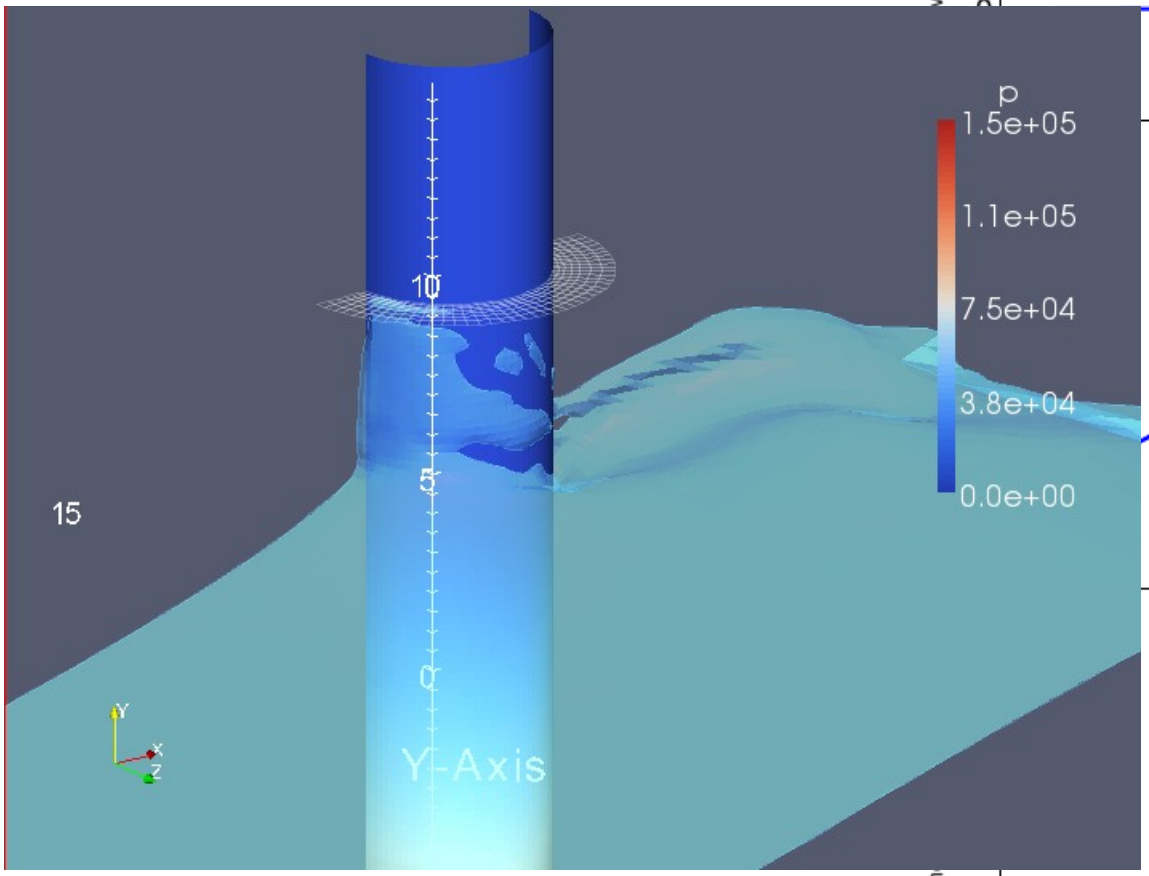

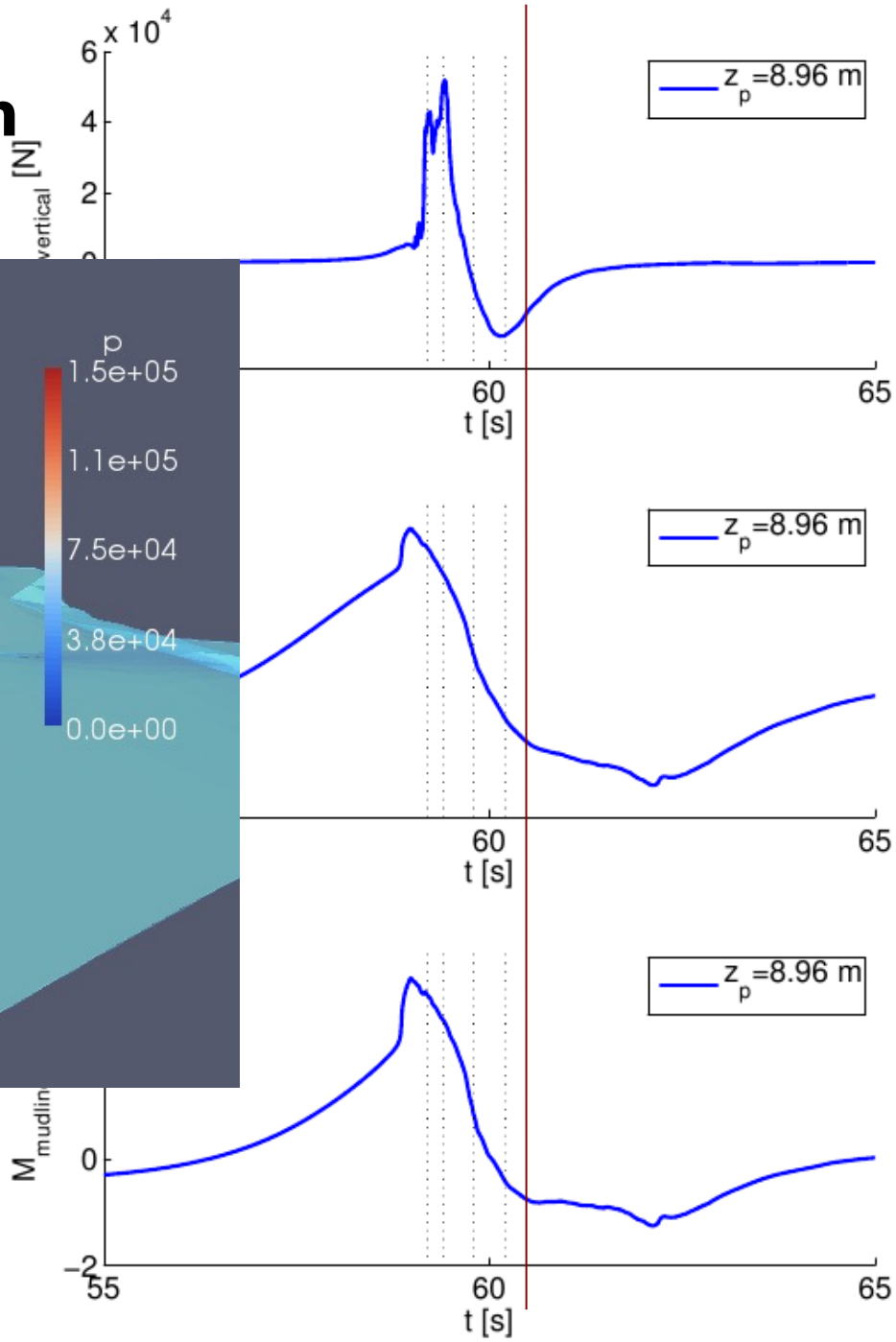

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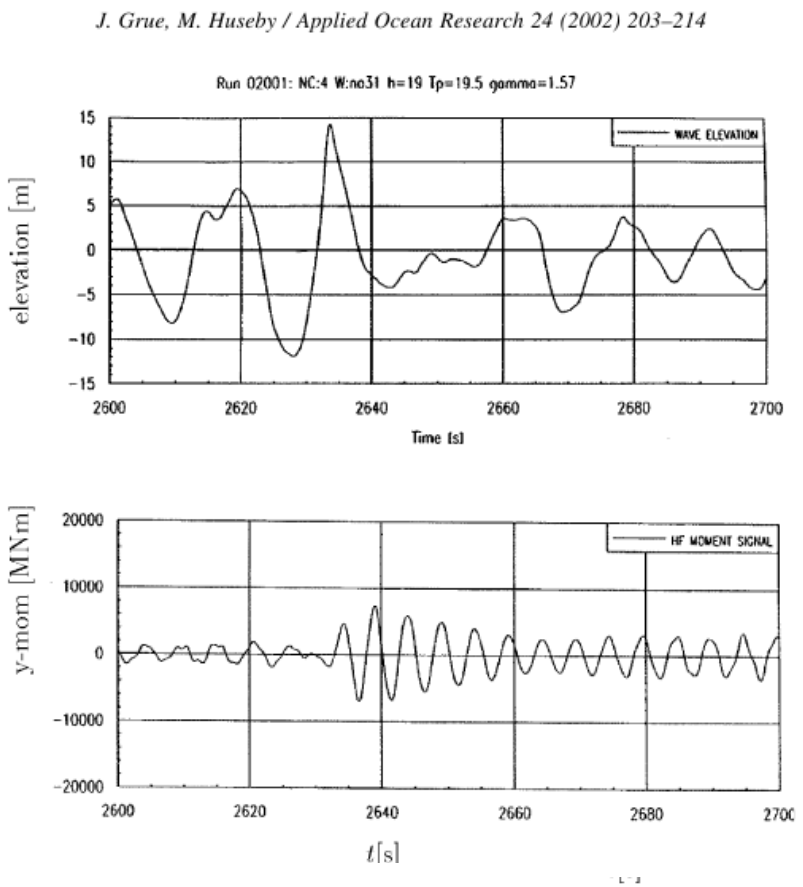
What is ringing?

Excitation of natural frequency by higher-harmonic forcing from nonlinear waves



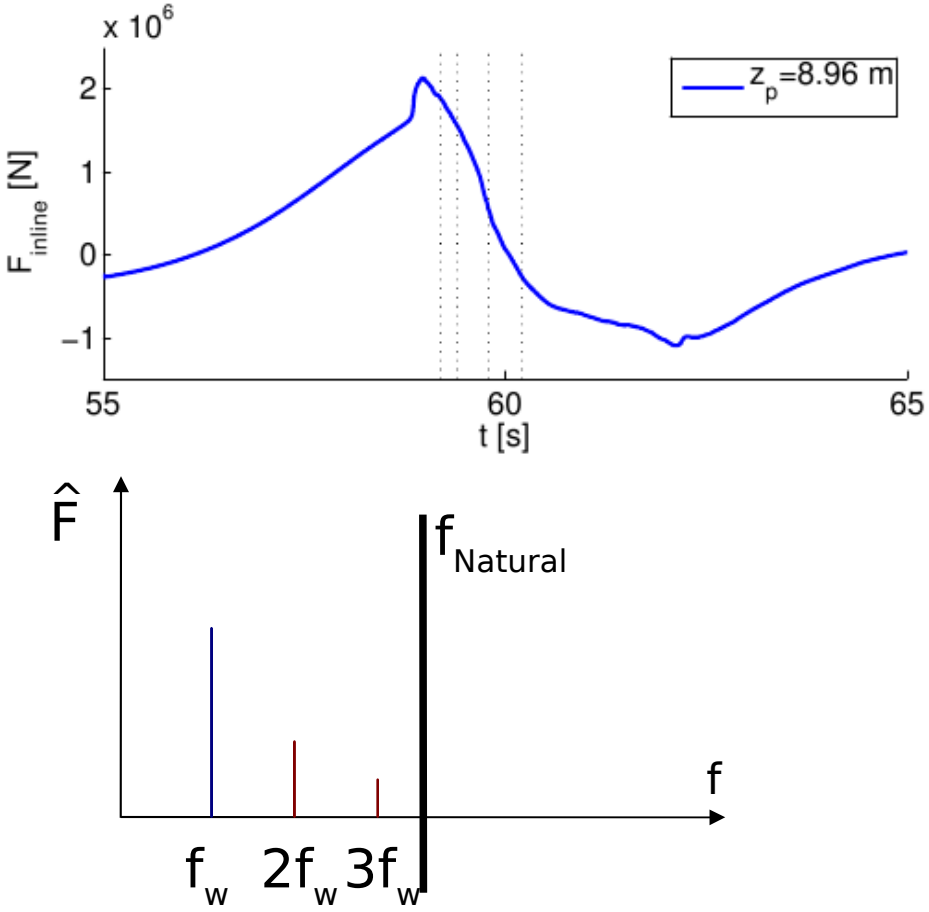
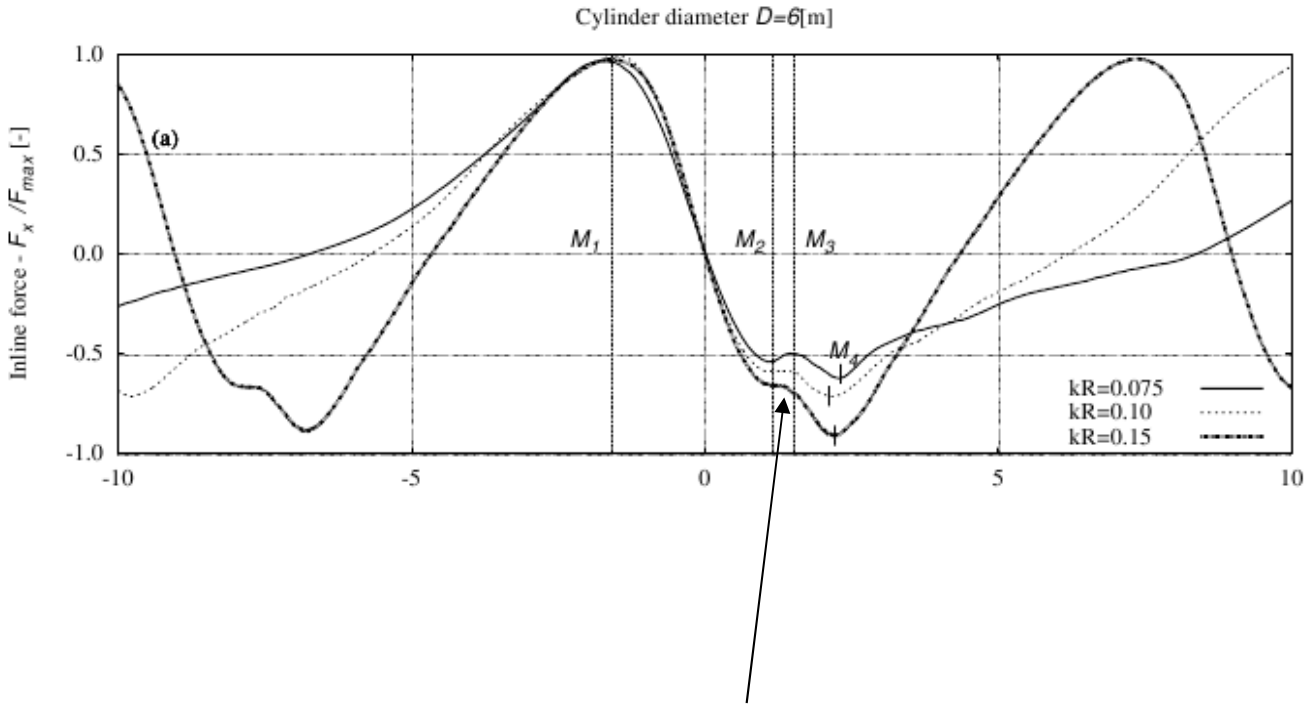


Fig. 8. Resonant build-up of vibrations in model tests [3, Fig. 3.3]. Bending moment of the Draugen GBS (lower). $(k\eta_m, kR) = (0.22, 0.13)$. Wave elevation (upper). Reproduced with kind permission by Shell.

Detailed calculation of forces from steep regular waves



secondary load cycle

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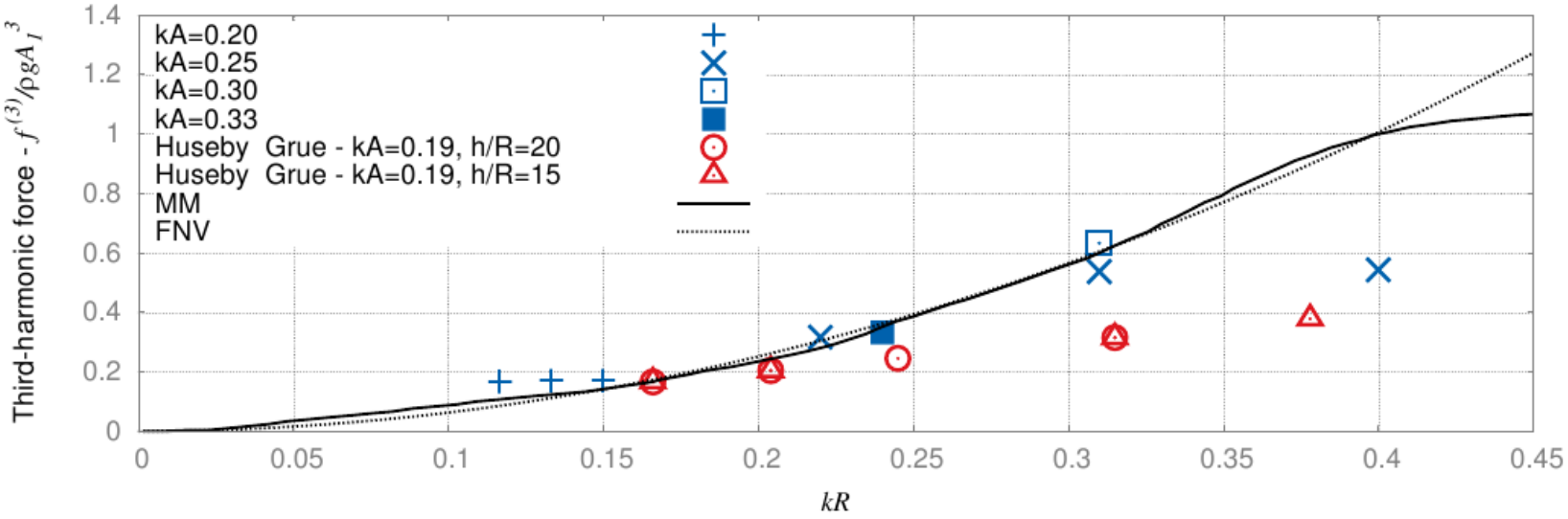
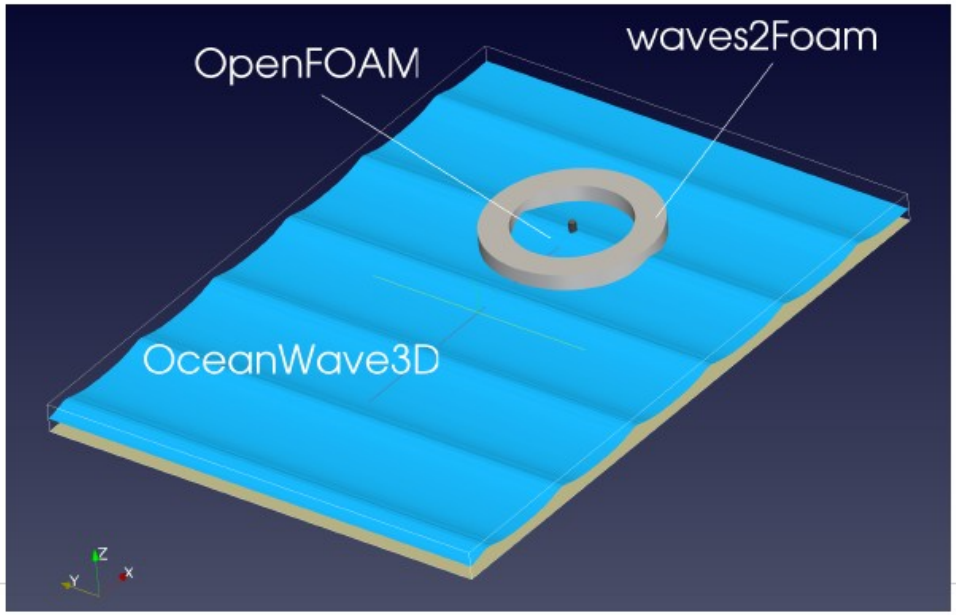
Third-harmonic force compared to FNV theory



Terp Paulsen et al
IWWWFB 2012

Coupling of OpenFOAM and OceanWave3D



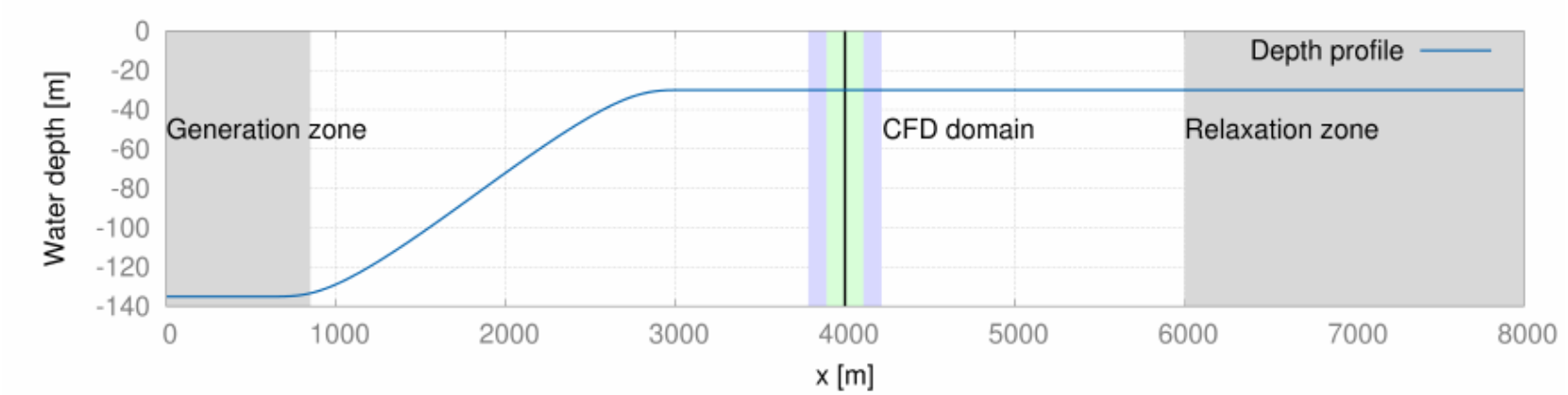
Compute outer flow field with potential flow wave model

Compute inner field with wave-structure interaction with CFD-VOF model

Terp Paulsen et al (2012)

Coupling of OpenFOAM and OceanWave3D

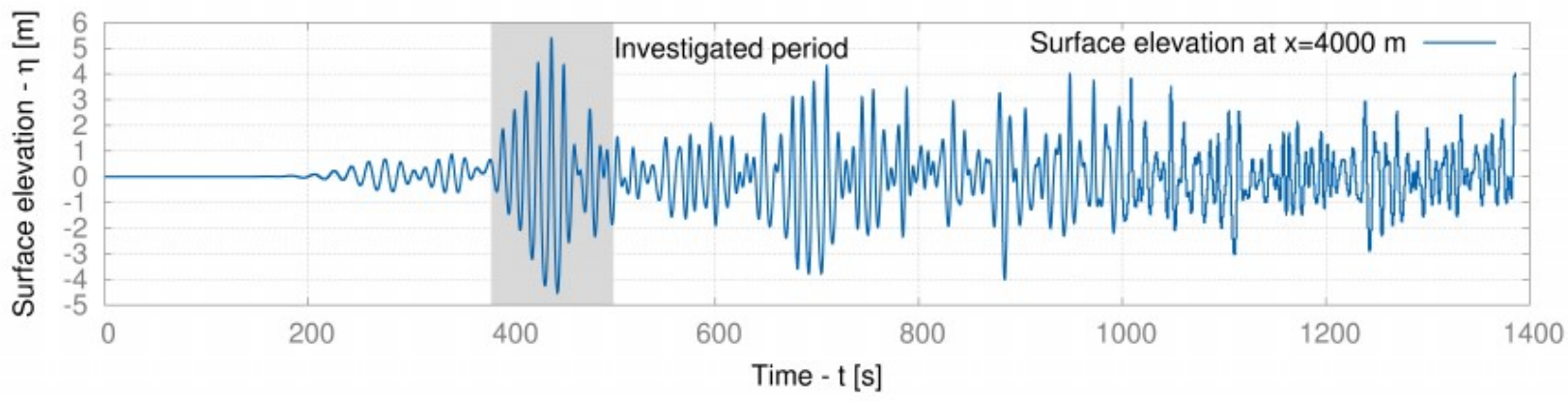
- Irregular waves: JONSWAP($T_p = 12\text{s}, H_s = 8\text{m}$)
- Large domain⇒ Impossible to resolve with CFD alone!
- Rather trivial test case as it serves as validation



Terp Paulsen et al (2012)

Coupling of OpenFOAM and OceanWave3D

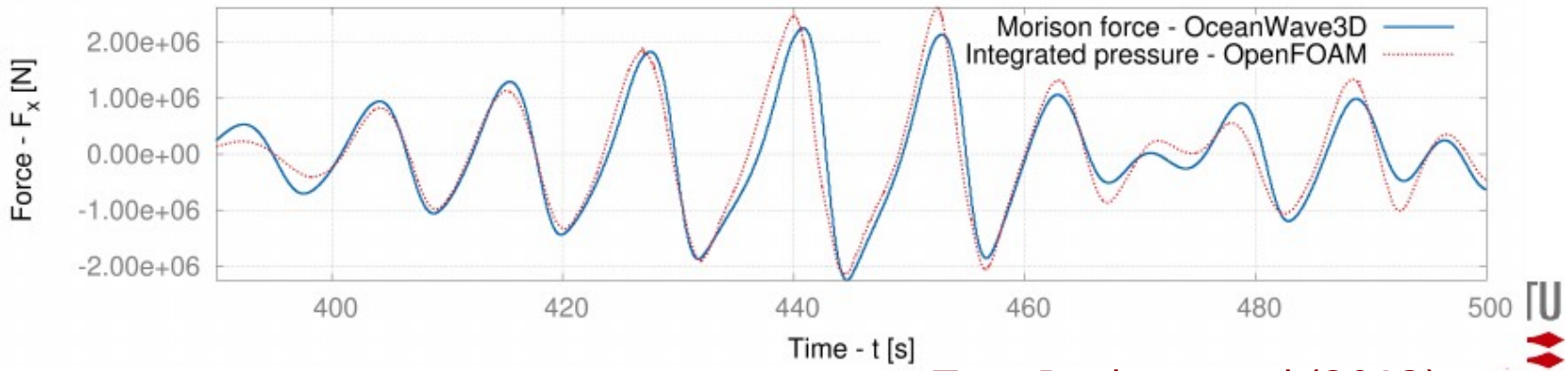
- 3hours times series of 2D irregular waves computed in hours with OceanWave3D
- Selected event analysed with OpenFOAM (~1day)



Terp Paulsen et al (2012)

Coupling of OpenFOAM and OceanWave3D

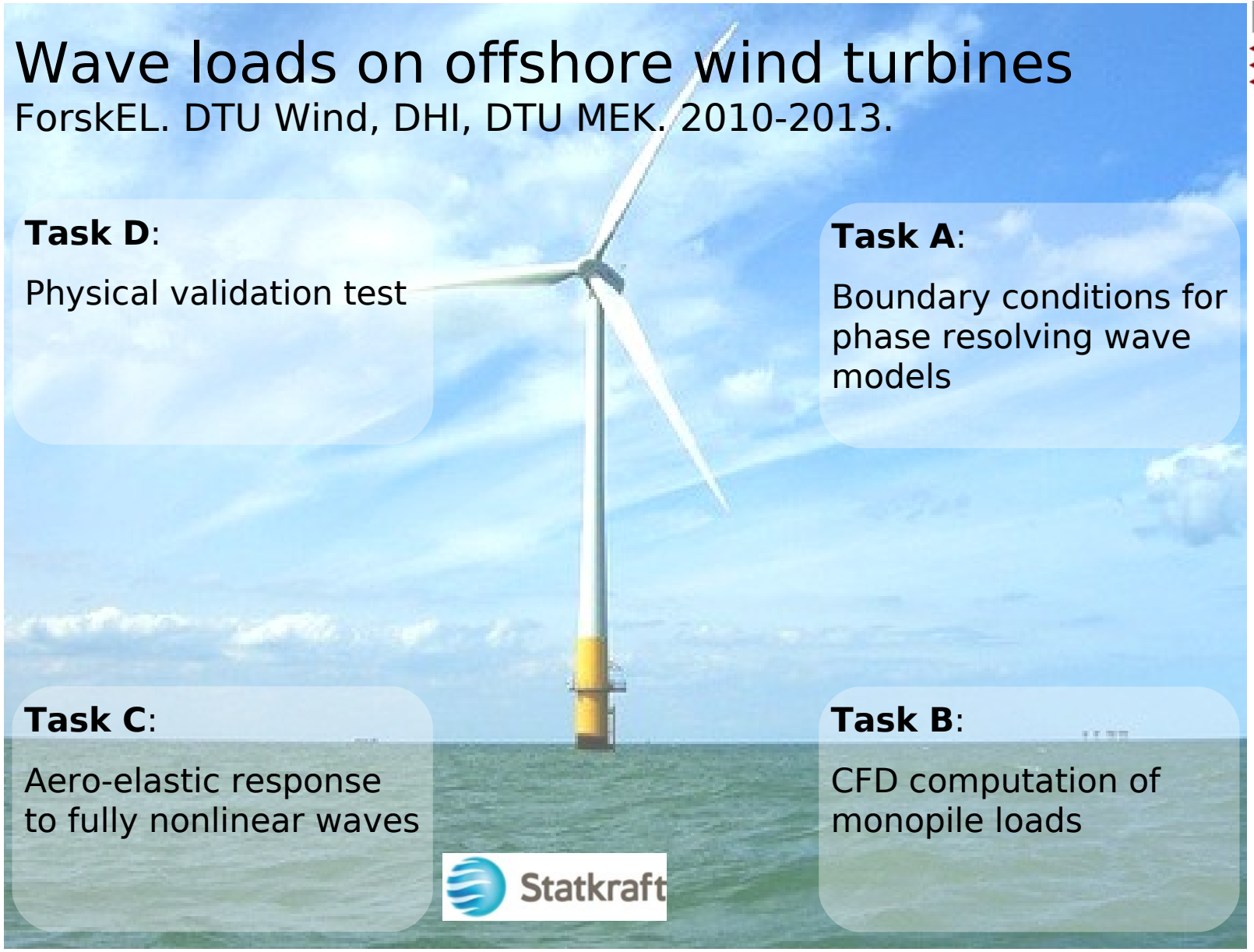
- Small "warmup" period for the CFD-computations: No initialization of pressure and pseudo air velocities
- Morison forces and CFD-computations agrees for small wave heights
- Discrepancies after passage of main event is attributed to diffraction effects



Terp Paulsen et al (2012)

Wave loads on offshore wind turbines

ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.



Task D:

Physical validation test

Task A:

Boundary conditions for phase resolving wave models

Task C:

Aero-elastic response to fully nonlinear waves

Task B:

CFD computation of monopile loads

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DTU Mechanical Engineering
Department of Mechanical Engineering

Wave loads Task D
Physical validation test

New tests at DHI with a rigid and a flexible structure

DHI:

Flemming Schlütter

Anders Wedel Nielsen

Jacob Tornfeldt Sørensen

DTU:

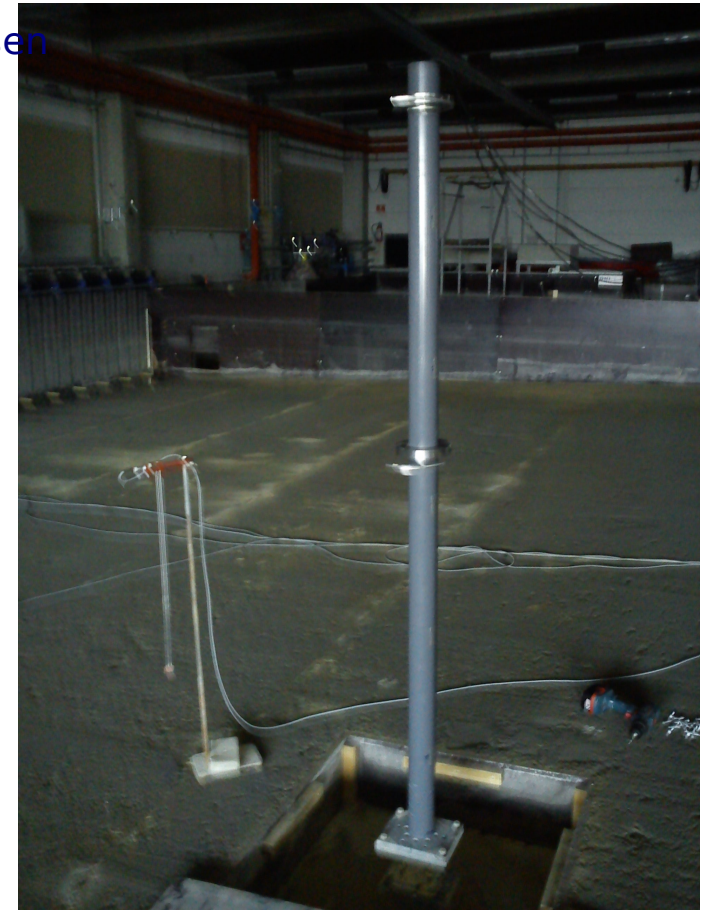
Henrik Bredmose

Torben Larsen

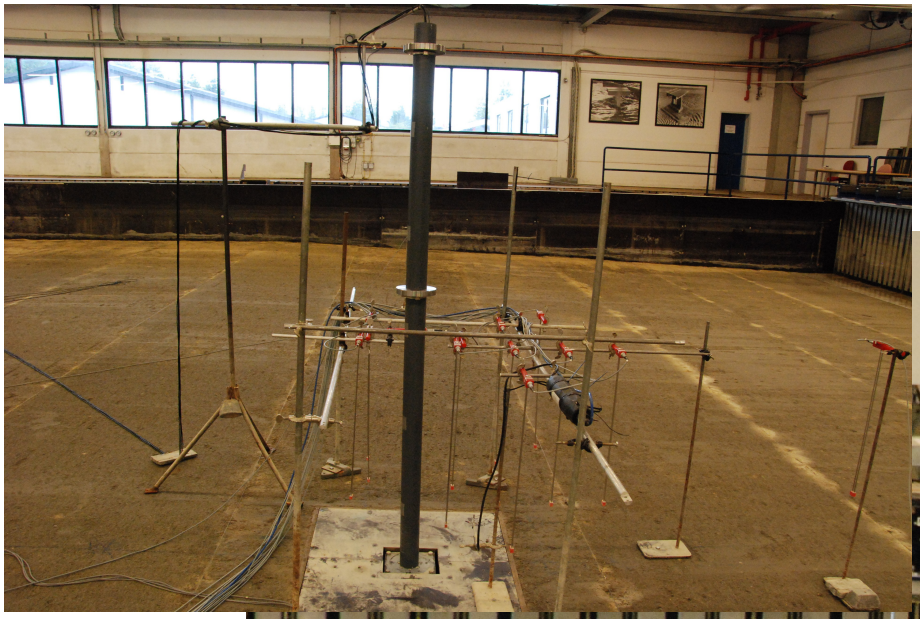
Signe Schløer

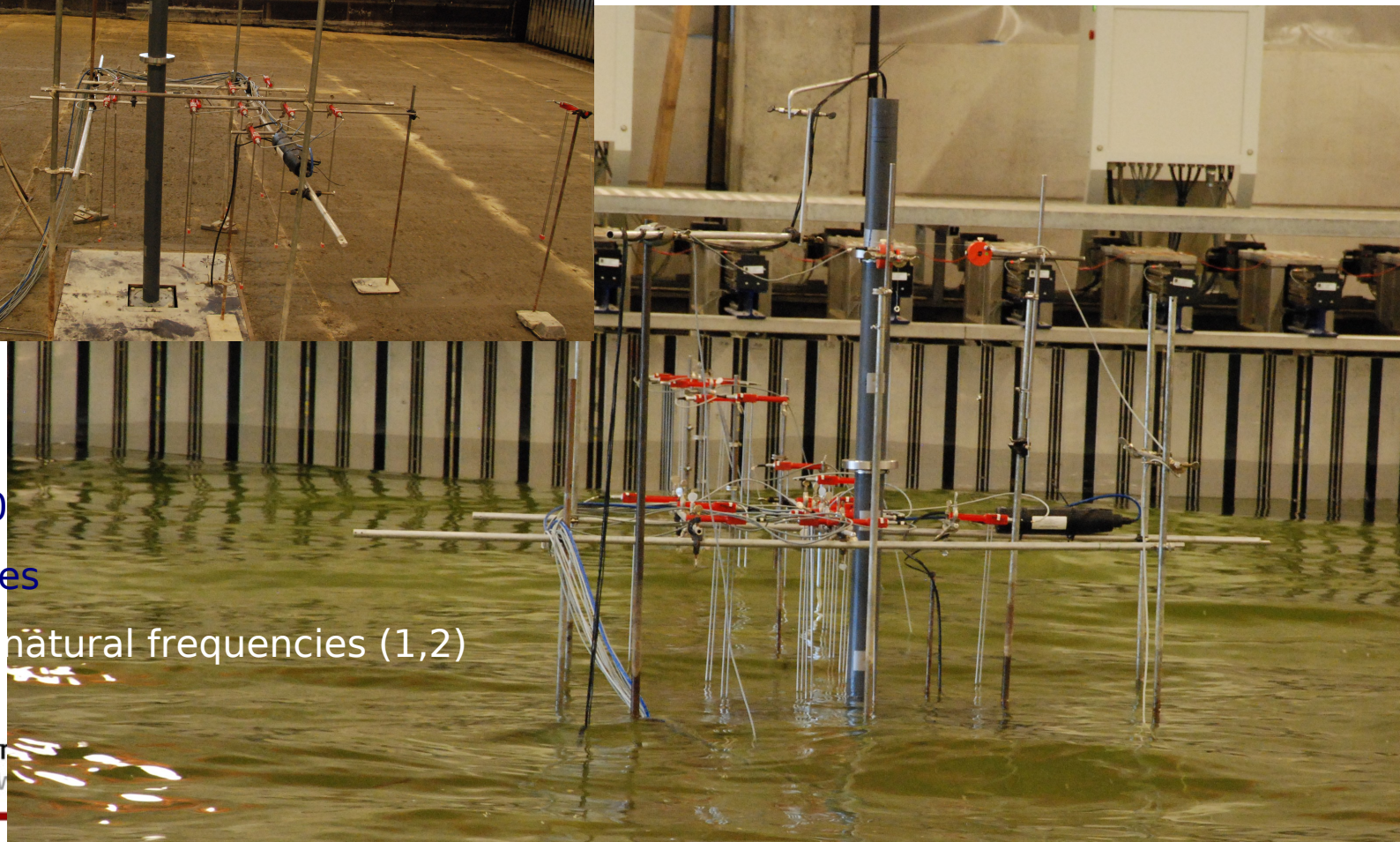
Bo Terp Paulsen

Harry Bingham



Wave loads Task D
Physical validation test





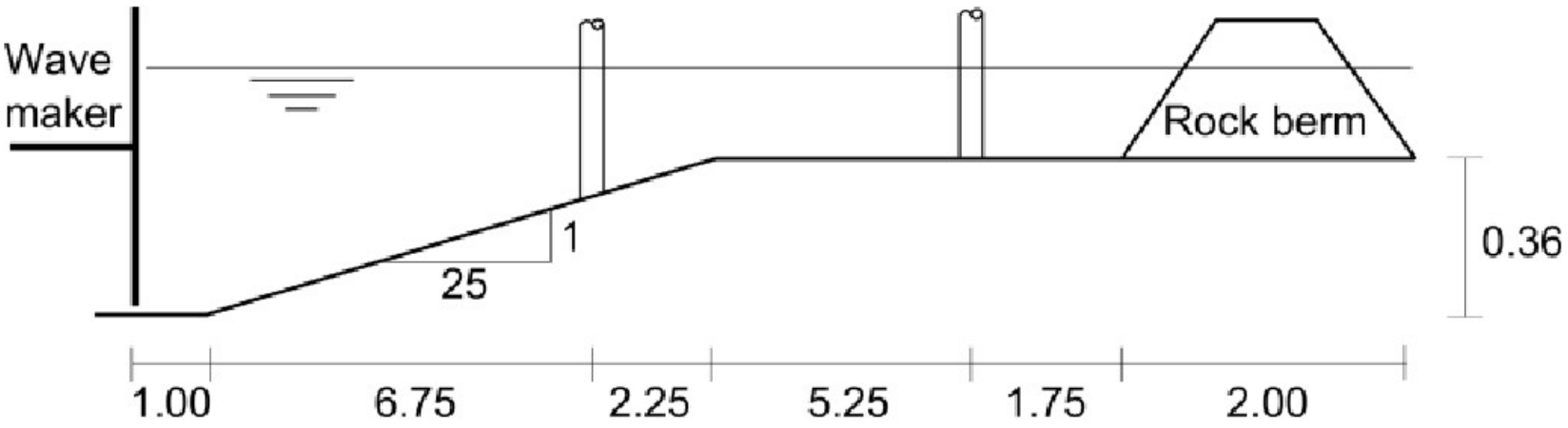
PVC pipe

Scale 1:80

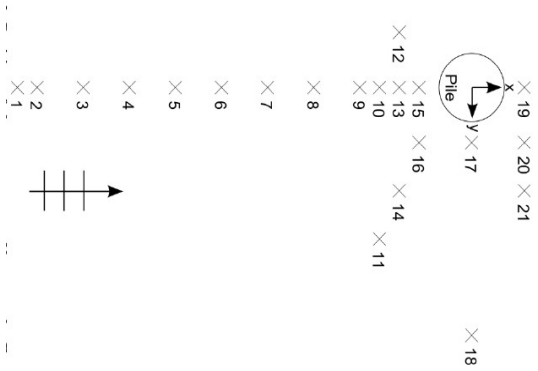
Two masses

→ right natural frequencies (1,2)

Experimental setup



side-view



top-view of wave gauges

Results and brief analysis for flexible pile

Irregular JONSWAP waves, unidirectional

h=20m

Tp=14s

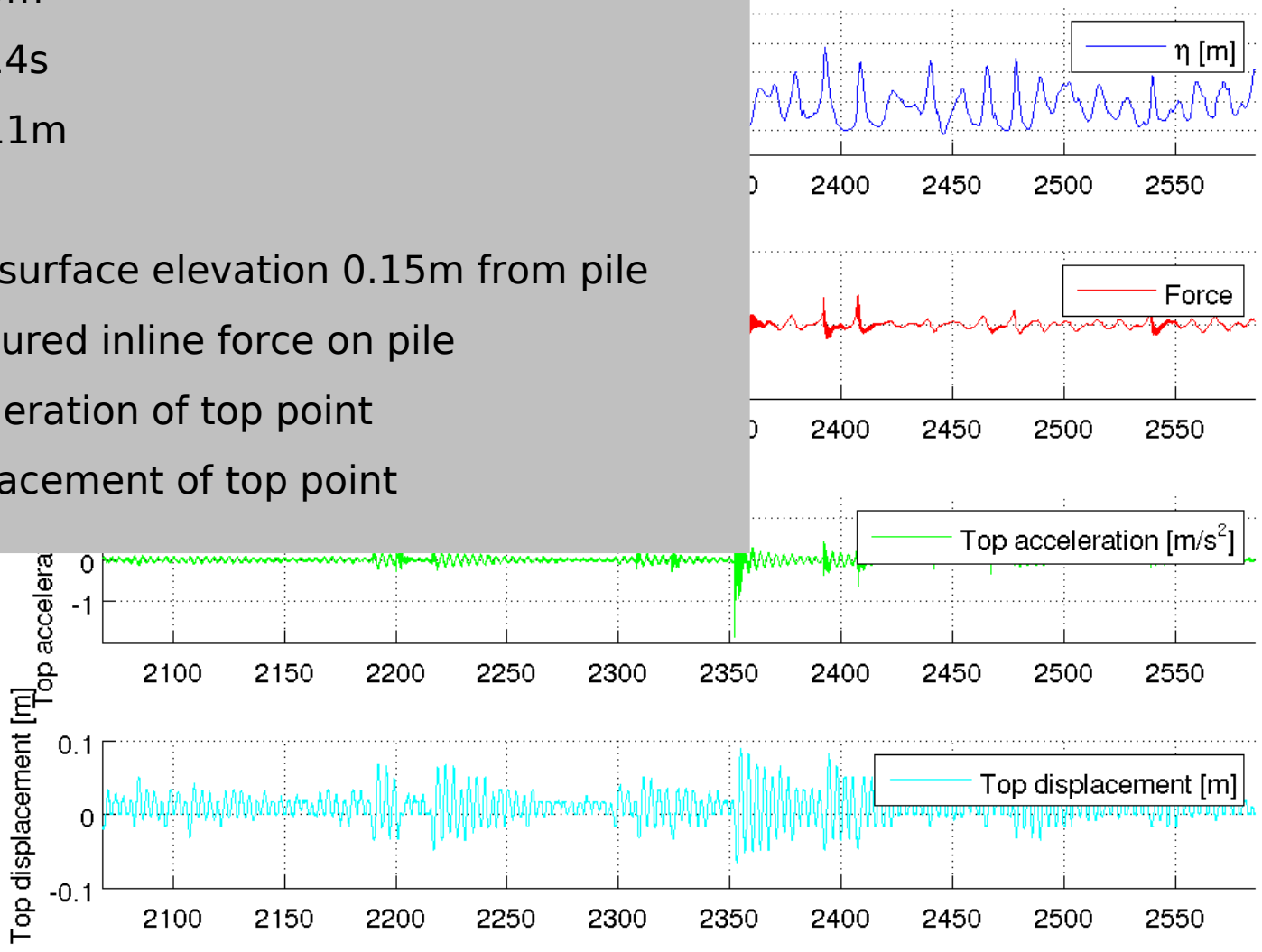
Hs=11m

Free surface elevation 0.15m from pile

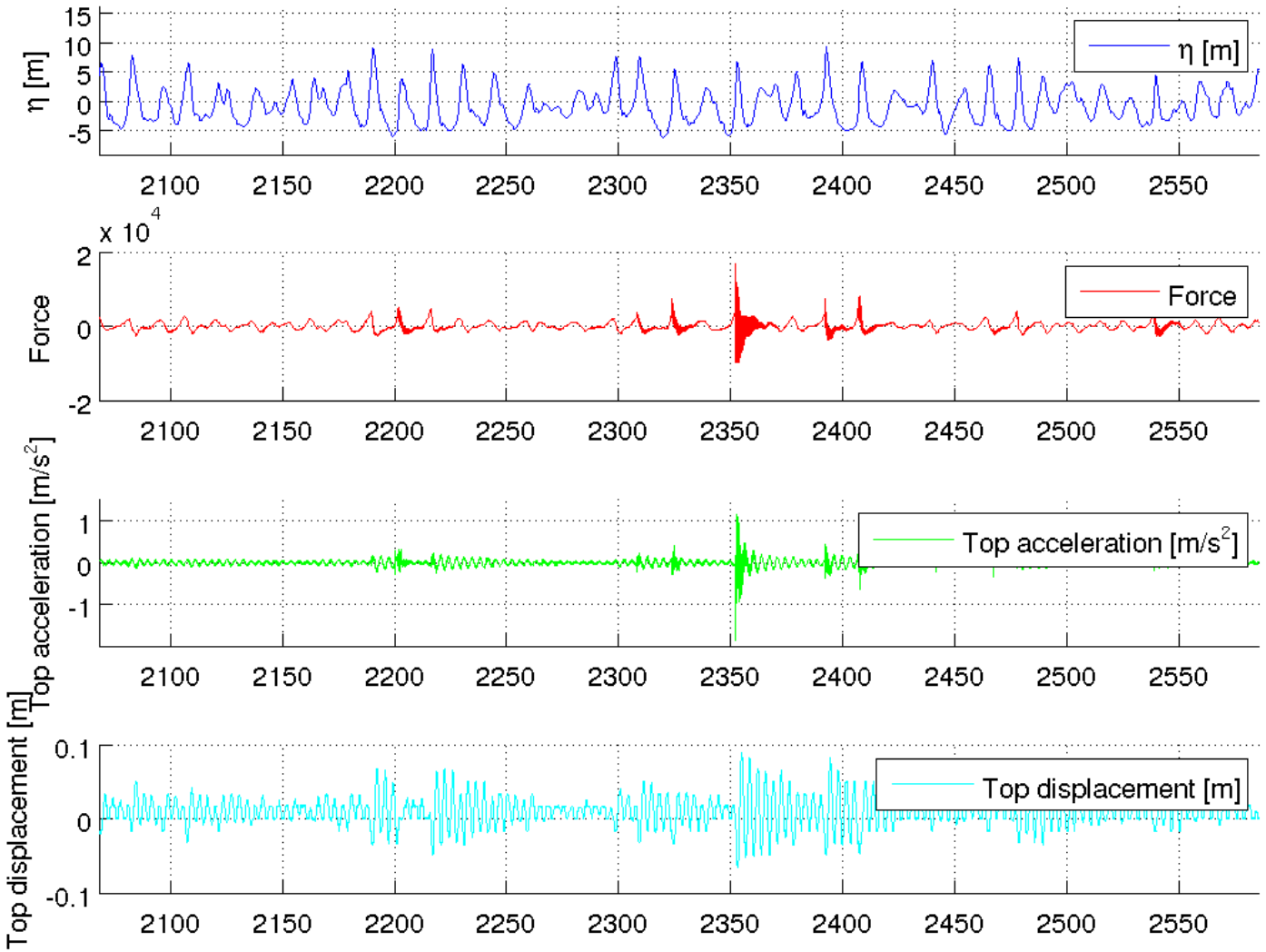
Measured inline force on pile

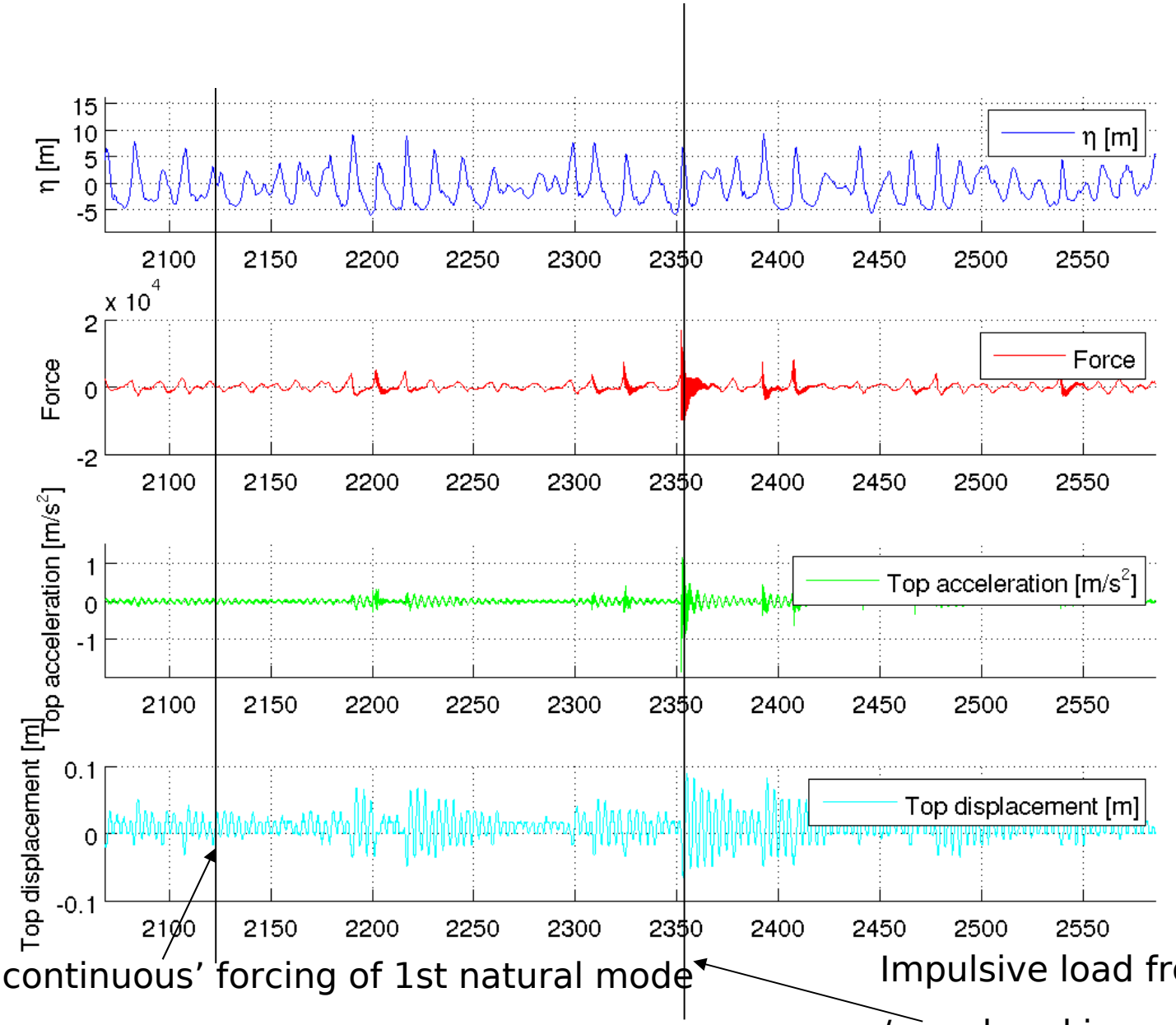
Acceleration of top point

Displacement of top point



Results and brief analysis

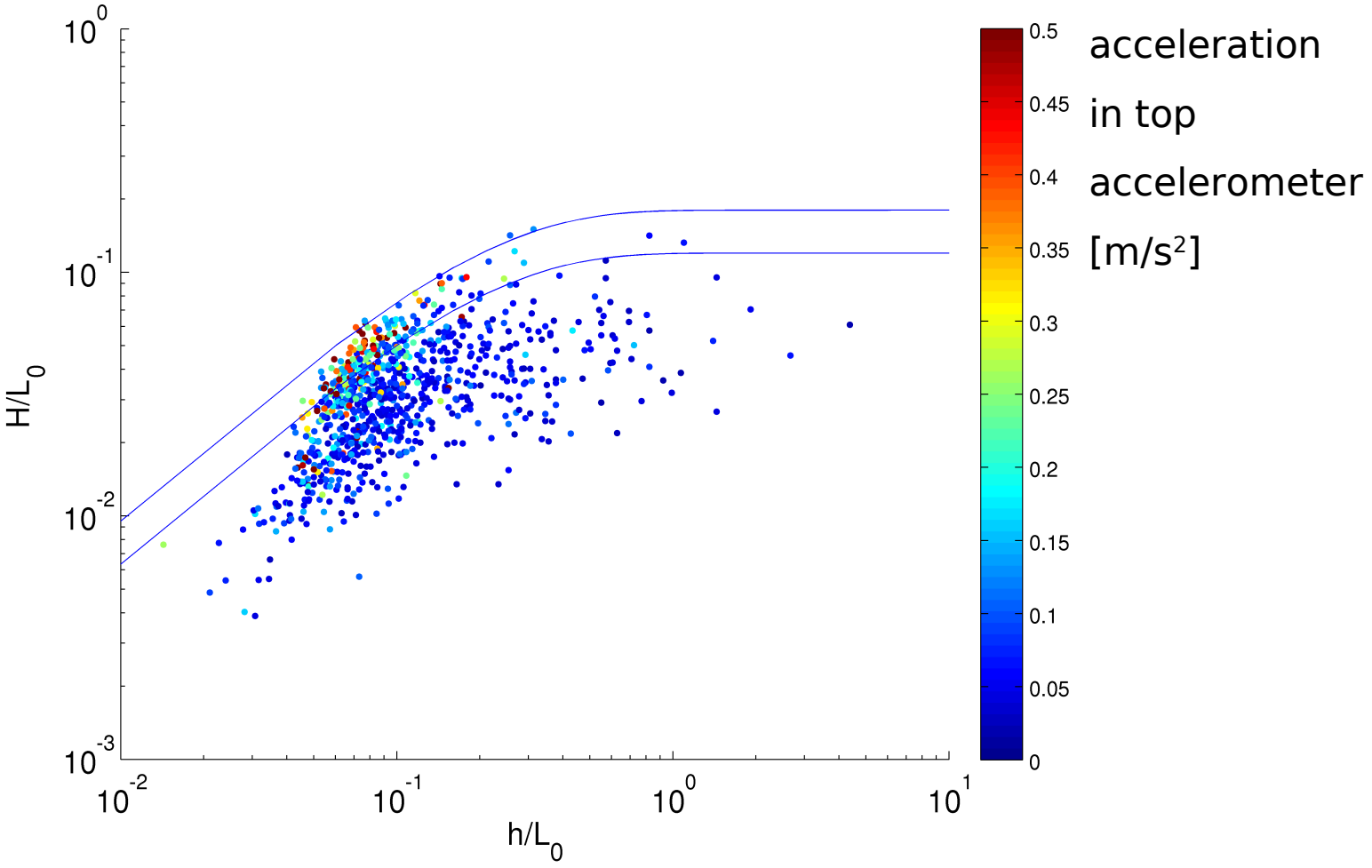




'continuous' forcing of 1st natural mode from wave-nonlinearity

Impulsive load from breaking /near breaking wave

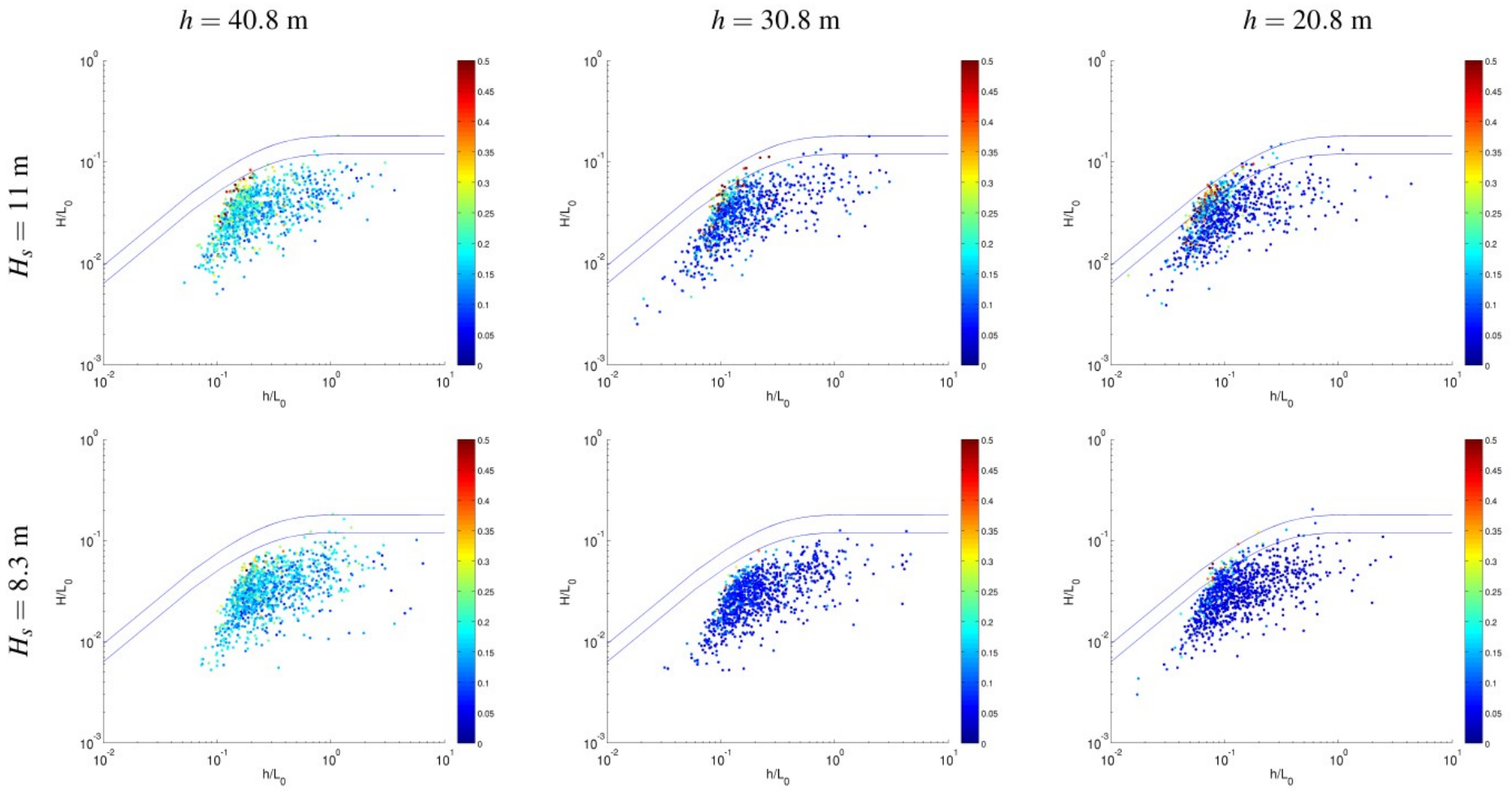
Which waves give the largest accelerations?



acceleration in top accelerometer [m/s^2]

Bredmose et al (OMAE 2013)

Which waves give the largest accelerations?



Bredmose et al (OMAE 2013)

Numerical reproduction of experiments

FEM model

Linear wave detection

Nonlinear wave transformation

Force model

$$\partial_t \eta = -\nabla\eta \cdot \nabla\tilde{\phi} + \tilde{w}(1 + \nabla\eta \cdot \nabla\eta),$$

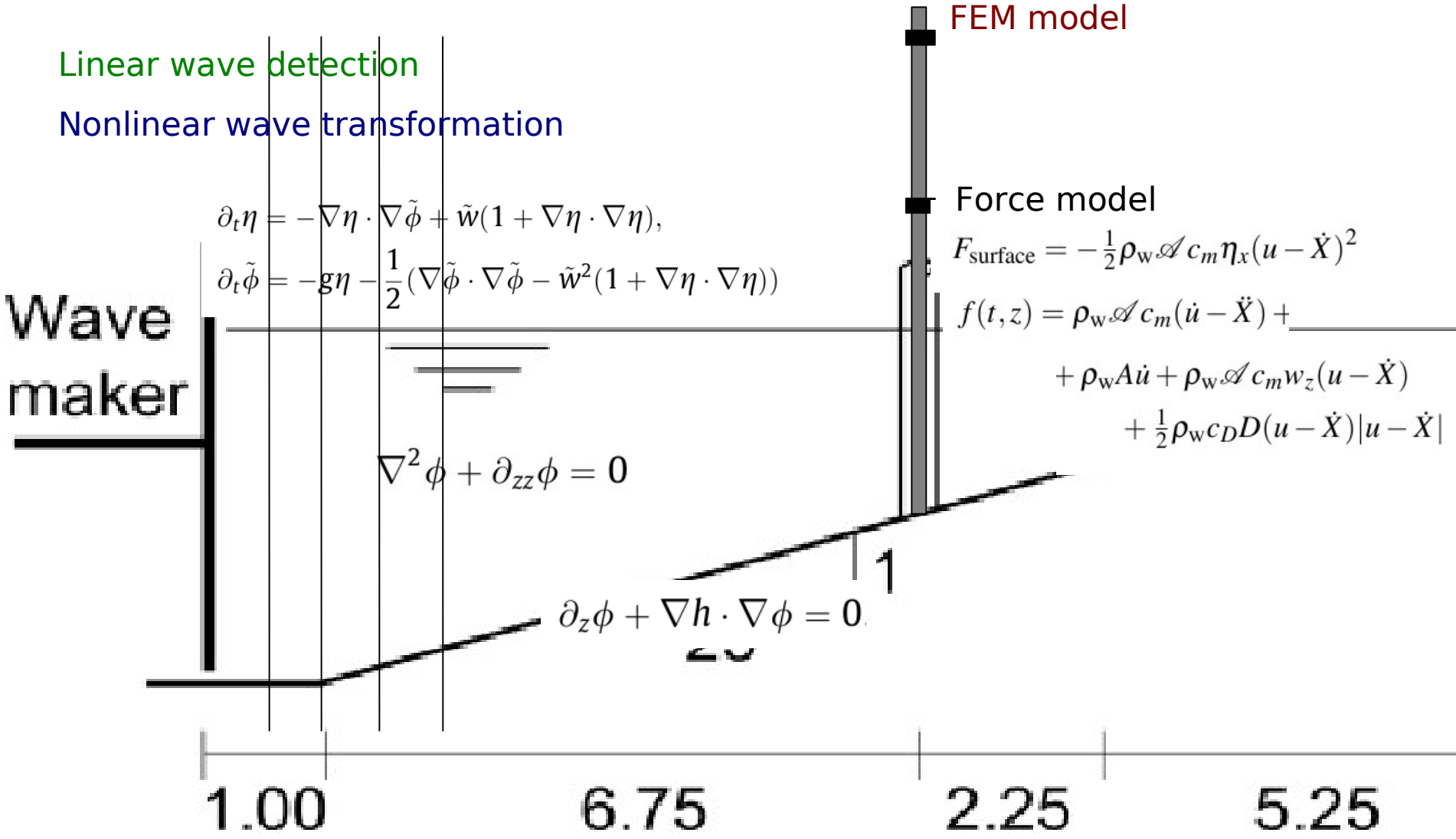
$$\partial_t \tilde{\phi} = -g\eta - \frac{1}{2}(\nabla\tilde{\phi} \cdot \nabla\tilde{\phi} - \tilde{w}^2(1 + \nabla\eta \cdot \nabla\eta))$$

$$F_{\text{surface}} = -\tfrac{1}{2}\rho_{\text{w}} \mathscr{A} c_m \eta_x (u - \dot{X})^2$$

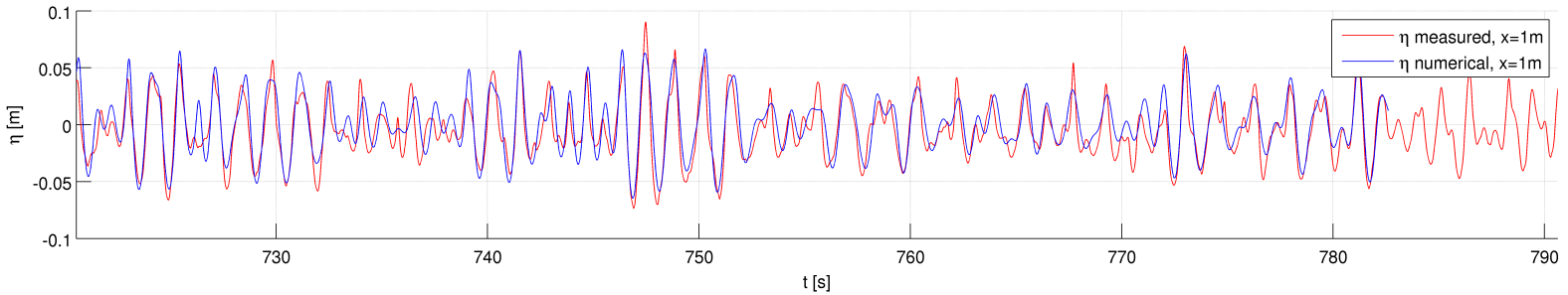
$$f(t,z) = \rho_{\text{w}} \mathscr{A} c_m (\dot{u} - \ddot{X}) +$$

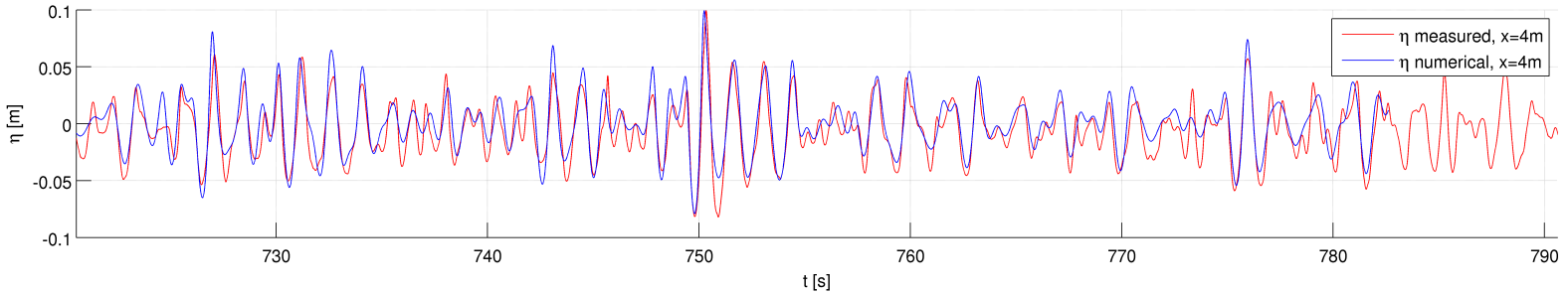
$$+ \rho_{\text{w}} A \dot{u} + \rho_{\text{w}} \mathscr{A} c_m w_z (u - \dot{X})$$

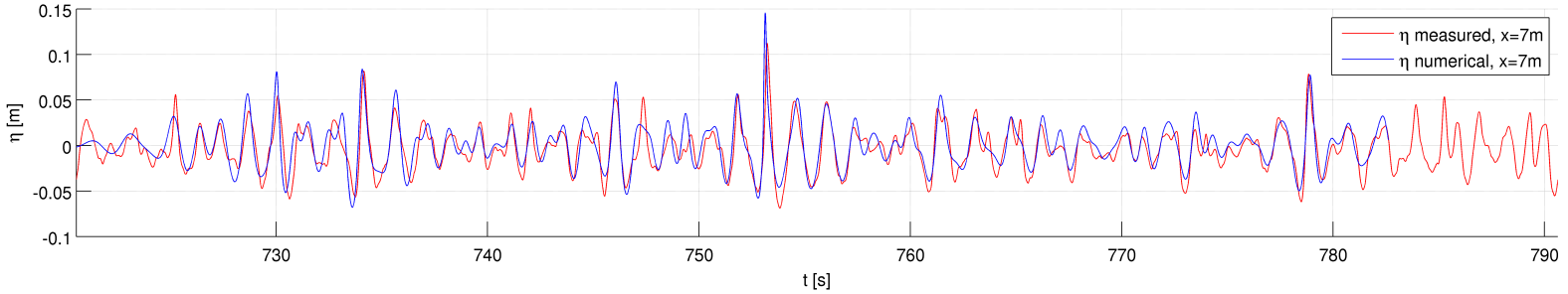
$$+ \tfrac{1}{2}\rho_{\text{w}} c_D D (u - \dot{X})|u - \dot{X}|$$



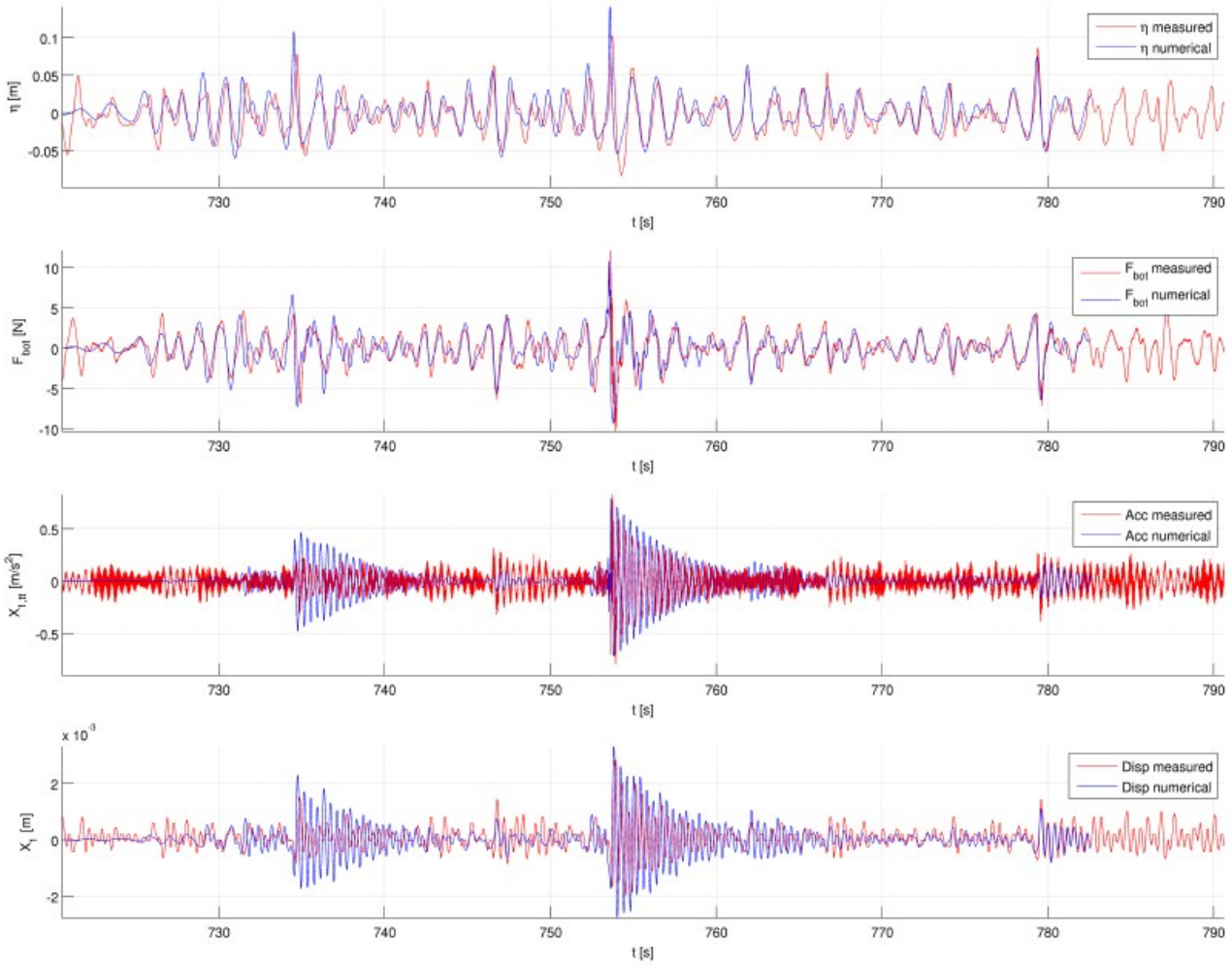
Wave transformation



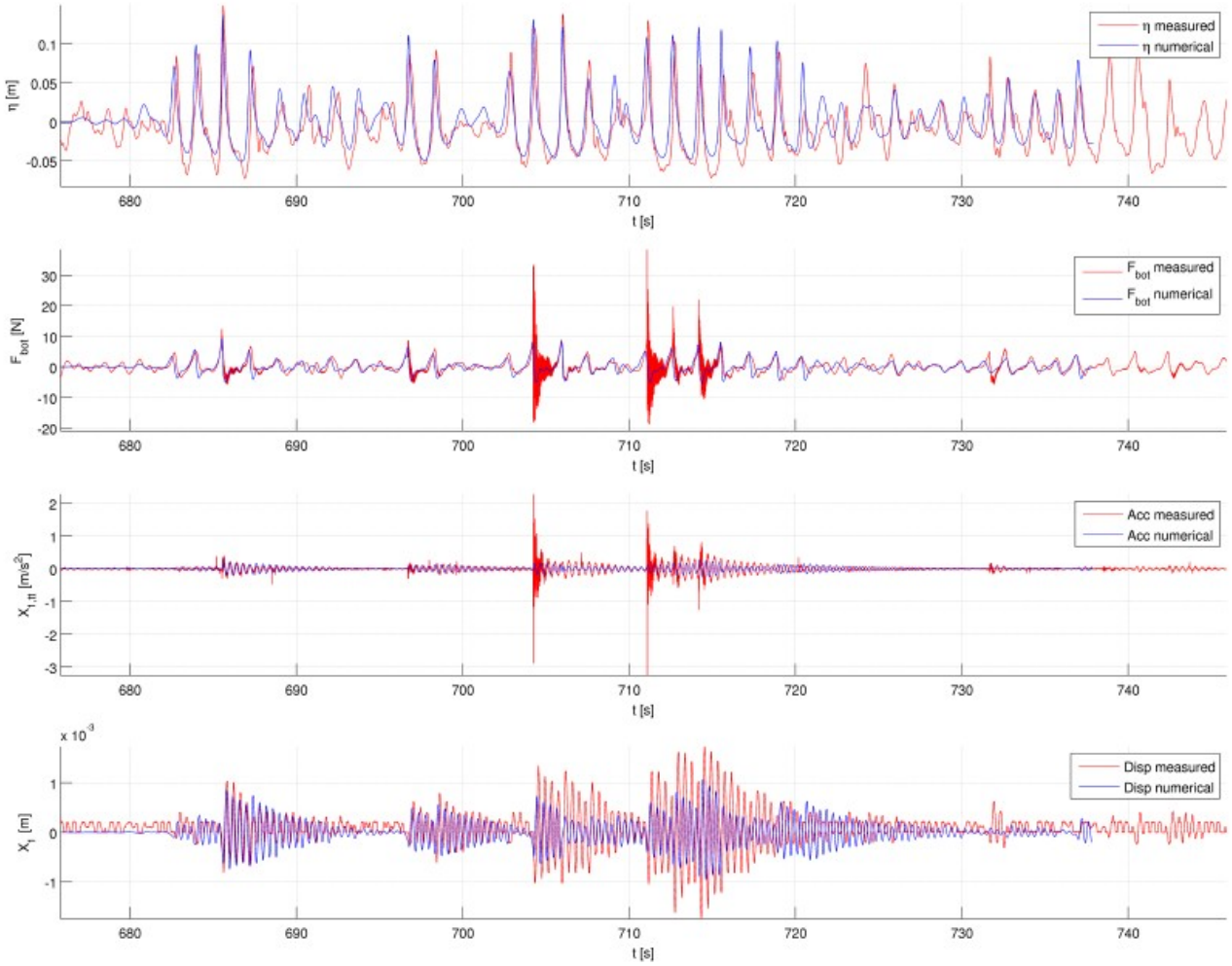




Response, h=40.8 m

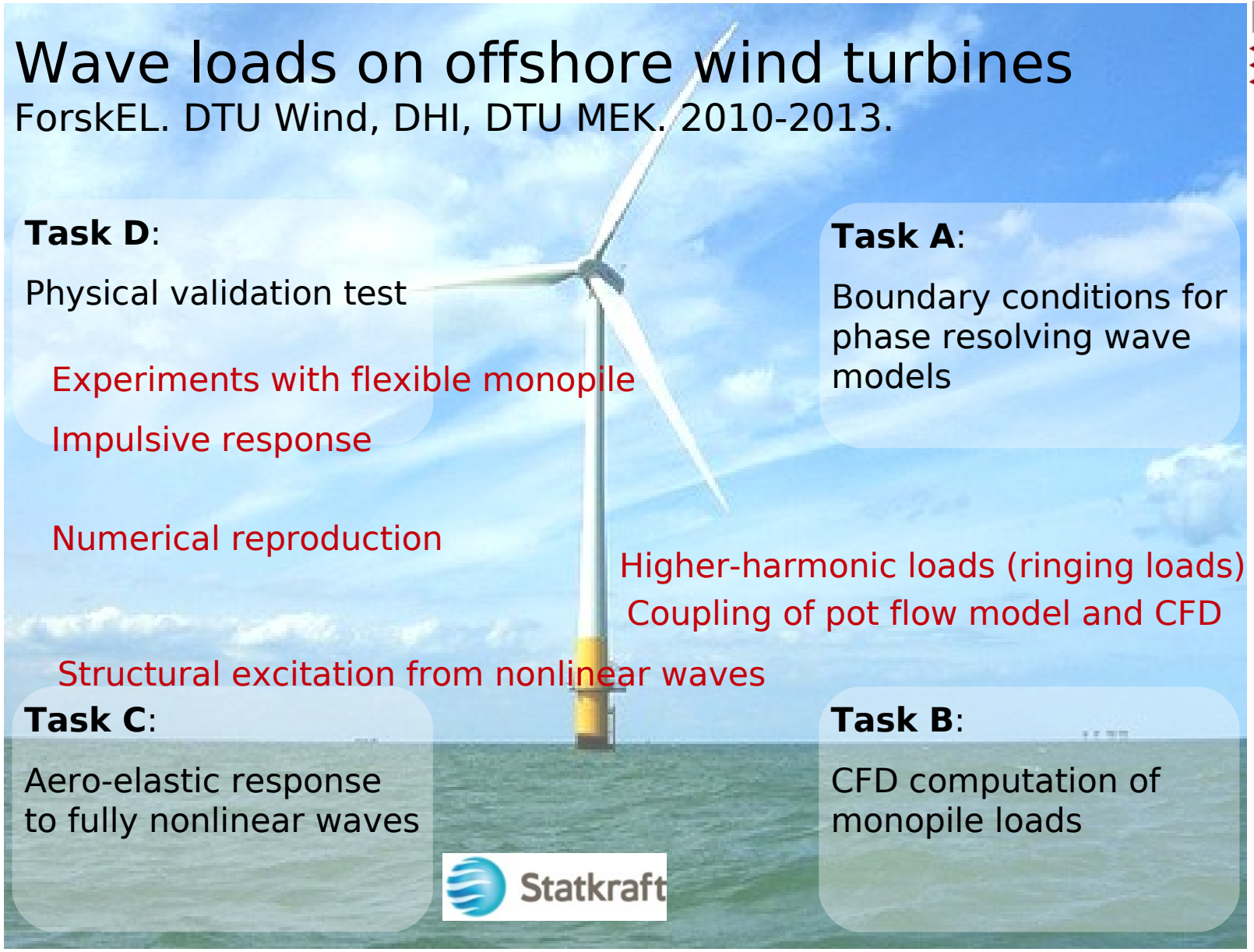


Response, h=20.8 m



Wave loads on offshore wind turbines

ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.



Task D:

Physical validation test

Experiments with flexible monopile

Impulsive response

Numerical reproduction

Task A:

Boundary conditions for phase resolving wave models

Higher-harmonic loads (ringing loads)

Coupling of pot flow model and CFD

Structural excitation from nonlinear waves

Task C:

Aero-elastic response to fully nonlinear waves

Task B:

CFD computation of monopile loads

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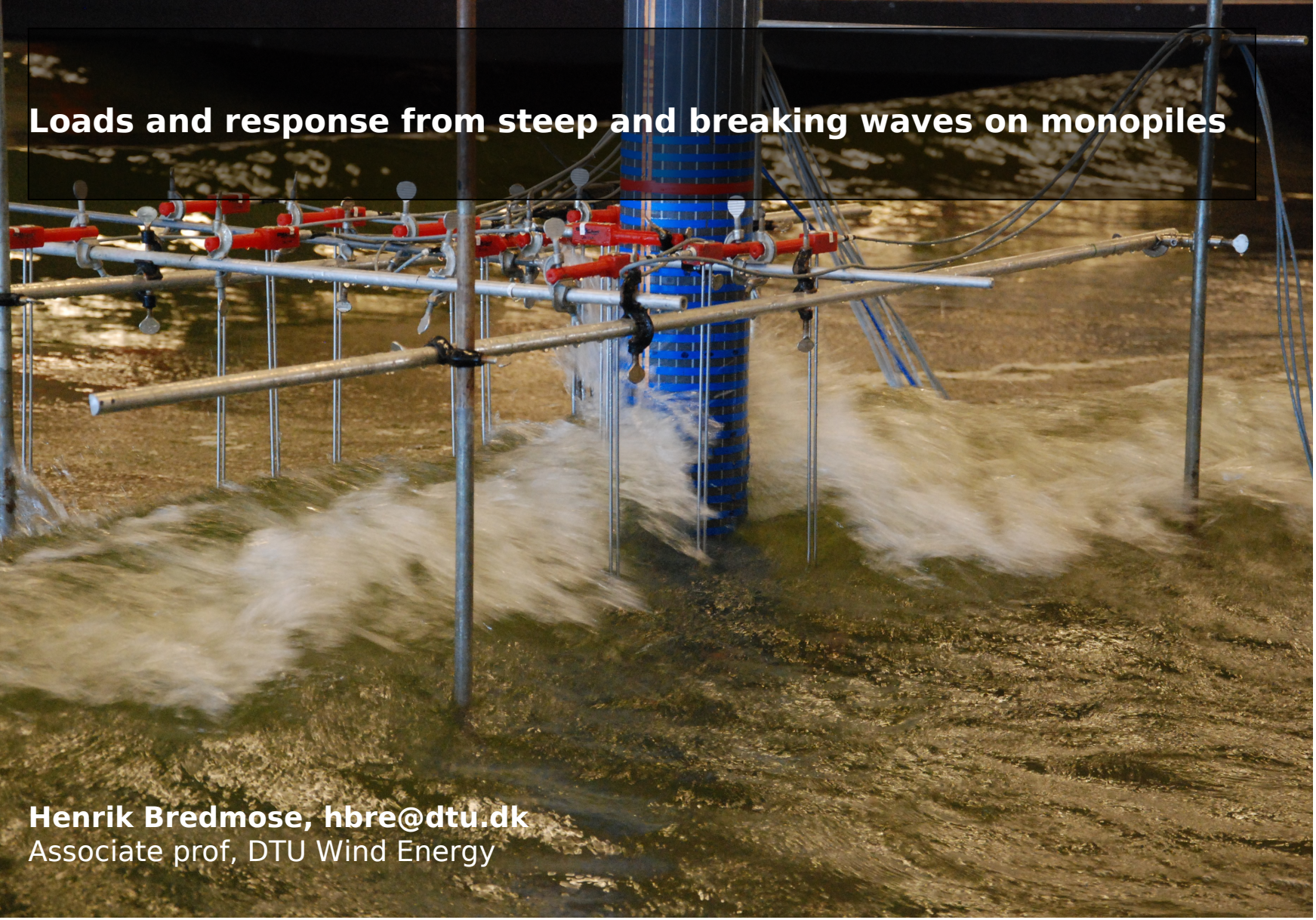
Loads and response from steep and breaking waves on monopiles



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